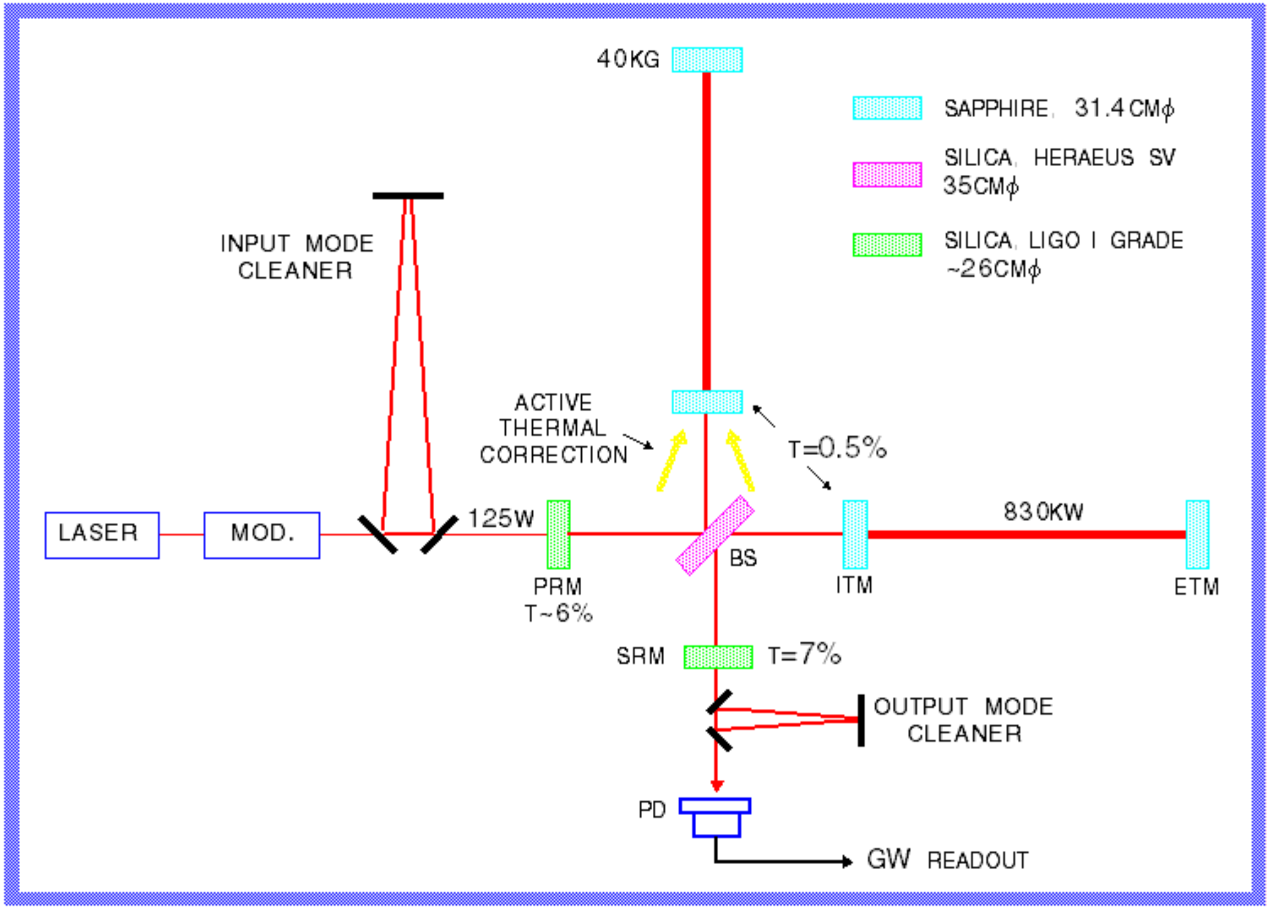
Input optics

"IO"

1. Input optics
2. EOM
3. Mode cleaner
4. Faraday
5. Other components

Advanced Interferometer



New features:

» Signal recycling

» 200-watt laser

» 40 kg test masses

» Larger beam size

» Higher arm finesse

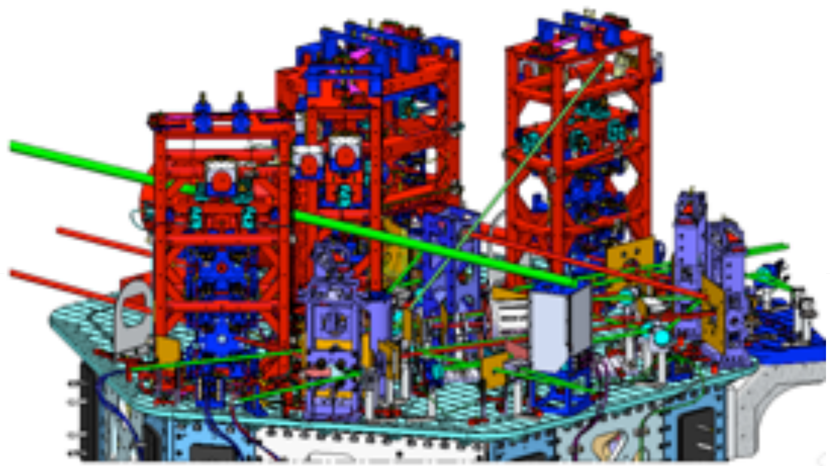
» Moderate recycling factor

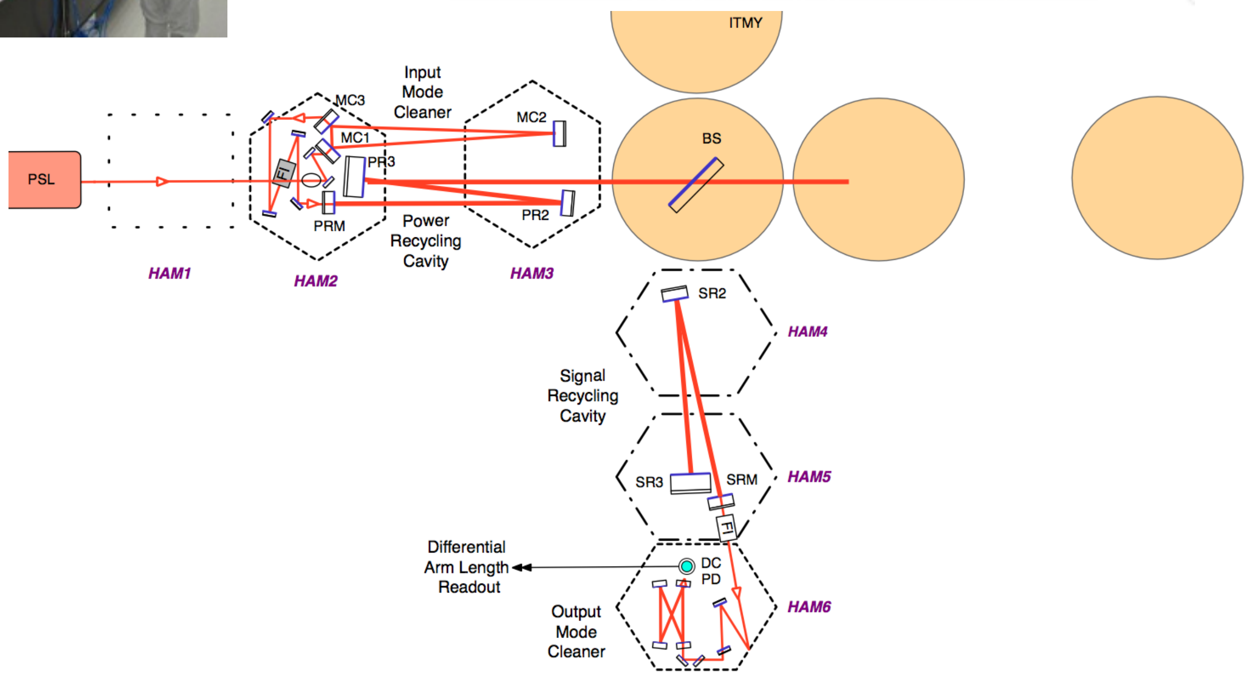
» Active thermal correction

» Better isolation from the ground

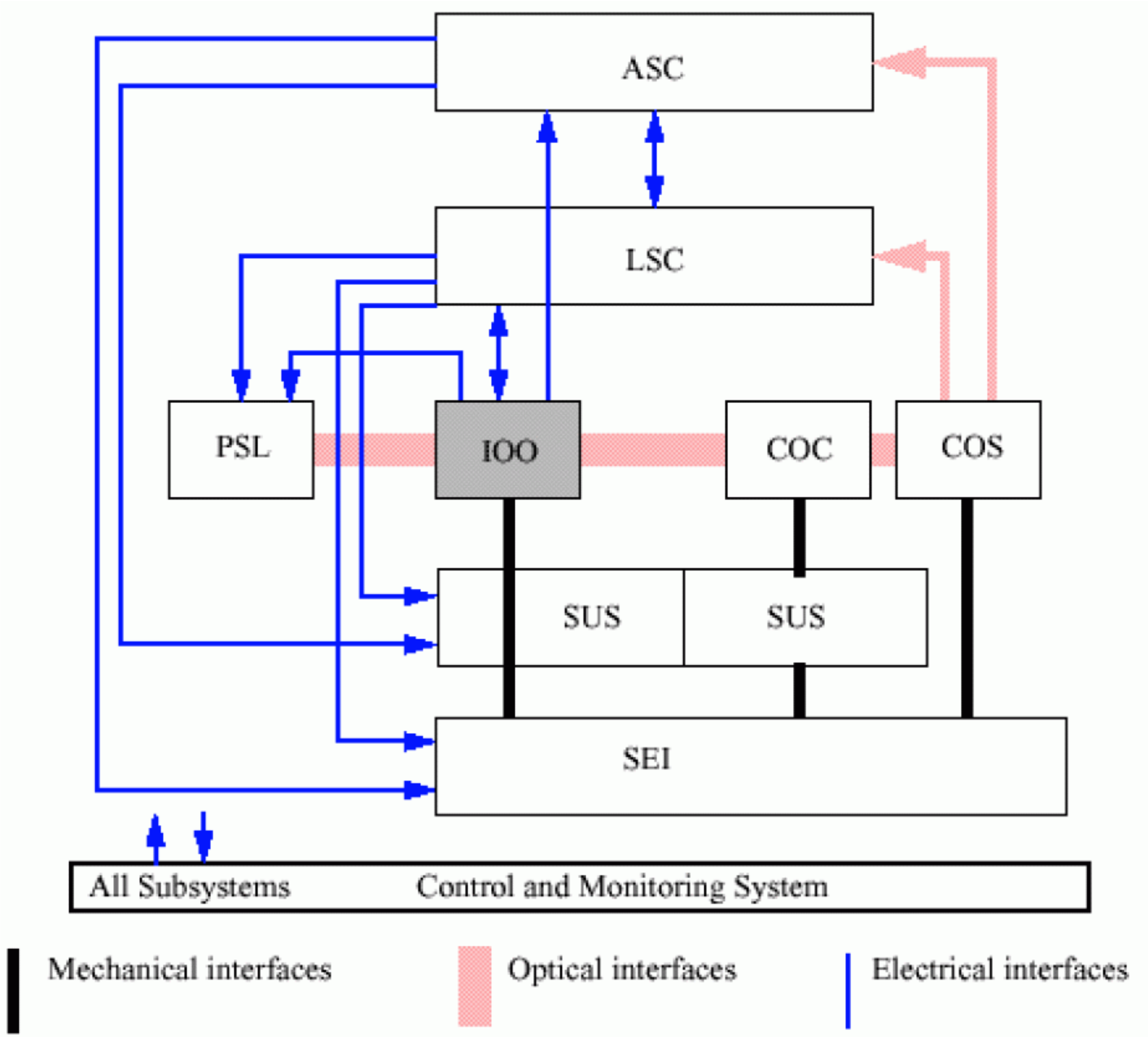
» Output mode cleaner

Advanced LIGO IO is very complex





IOO = “input optics”

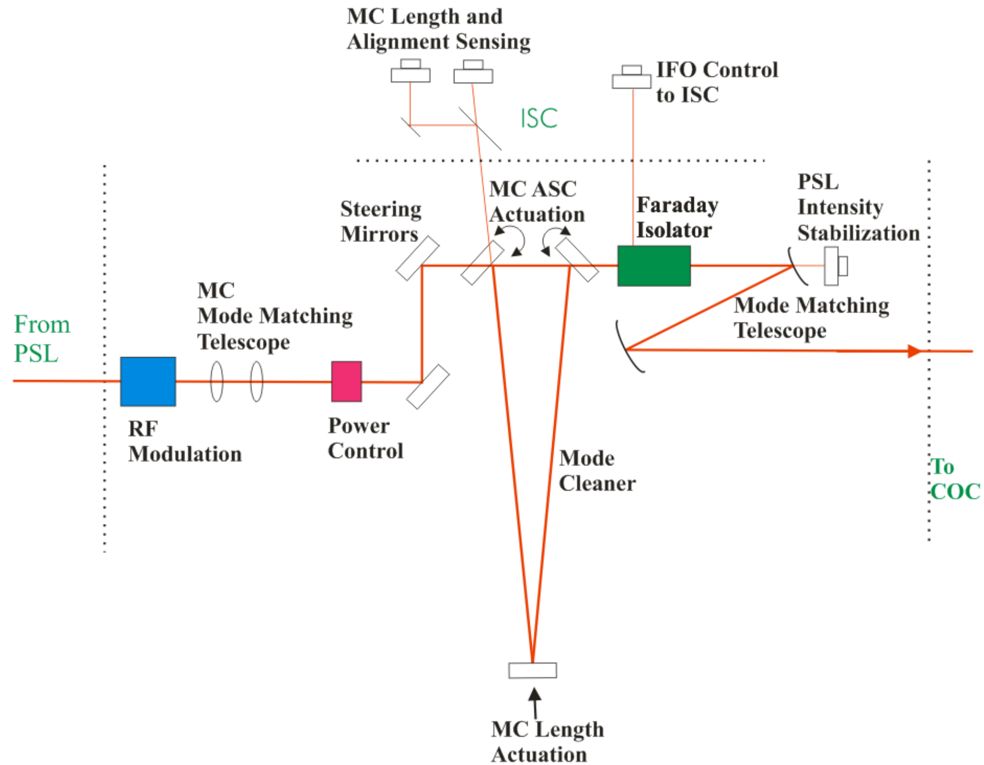


The input optics (IO)

The input optics (IO) conditions the PSL laser light and delivers it to the interferometer.

It provides:

- RF modulation for length and alignment control functions
- Power control
- Laser mode cleaning and frequency stabilization
- Isolation of laser from interferometer reflected light
- Optical signal distribution to length and alignment control
- Mode matching to recycling and arm cavities
- Design and fabrication of small PRMs and SRMs



PSL = pre-stabilized laser
COC = core optical components
IMC = input mode cleaner
ISC = interferometer sensing and control
PRM = power recycling mirror
SRM = signal recycling mirror

IO Schedule Highlights

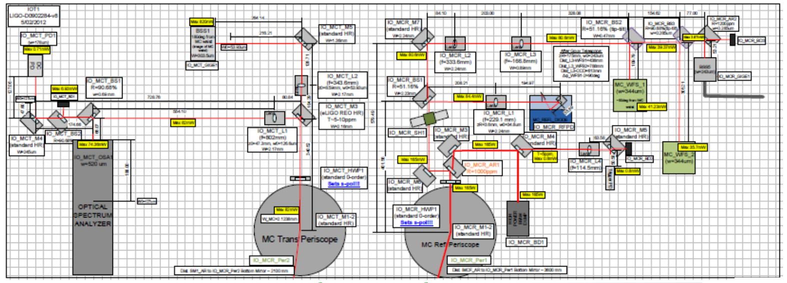
Activity Name	Start	Finish
LIGO LIGO Lab Program - AdvL Current	21-Aug-00 A	03-Apr-12
LIGO.3 Advanced LIGO Development	21-Aug-00 A	15-Apr-11
LIGO.3.05 Input Optics (IO)	21-Aug-00 A	15-Apr-11
LIGO.3.05.1 IO Management	21-Aug-00 A	23-Feb-10 A
LIGO.3.05.1.1 IO Development Management	21-Aug-00 A	23-Feb-10 A
LIGO.3.05.3 IO Design	21-Aug-00 A	15-Apr-11
LIGO.3.05.3.1 IO Conceptual Design/Requirements	21-Aug-00 A	07-May-02 A
LIGO.3.05.3.2 IO Preliminary Design	07-May-02 A	21-Aug-07 A
LIGO.3.05.3.3 IO Final Design	07-Apr-06 A	15-Apr-11
LIGO.4 Advanced LIGO Project	02-Sep-08 A	03-Apr-12
LIGO.4.05 Input Optics (IO)	02-Sep-08 A	03-Apr-12
LIGO.4.05.1 IO Management	02-Sep-08 A	03-Apr-12
LIGO.4.05.1.2 IO Fabrication Management	02-Sep-08 A	03-Apr-12
LIGO.4.05.4 IO Fabrication	02-Sep-08 A	03-Apr-12
LIGO.4.05.4.1 IO Modulation System	17-Feb-09 A	28-Sep-11
LIGO.4.05.4.2 IO Mode Cleaner and MMT Assemblies	02-Sep-08 A	03-Apr-12
LIGO.4.05.4.3 IO Optical Isolation	15-Feb-10 A	28-Sep-11
LIGO.4.05.4.4 IO Baffles	03-May-10 A	10-Feb-12

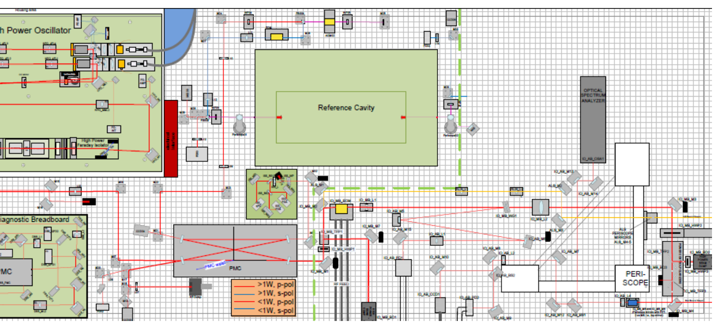
- Overall IO Final Design substantially completed in Feb 2010
  - May 2011 is for baffles (additional scope), installation
- IO Project phase began in Sept 08
  - Optics procurement (input mode cleaner, recycling mirrors, steering and mode-matching mirrors) is largest component of the project
  - Well underway; on track to meet installation schedule

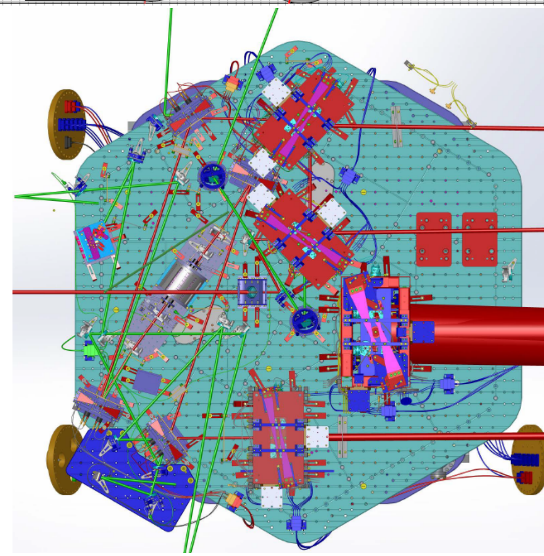
LIGO

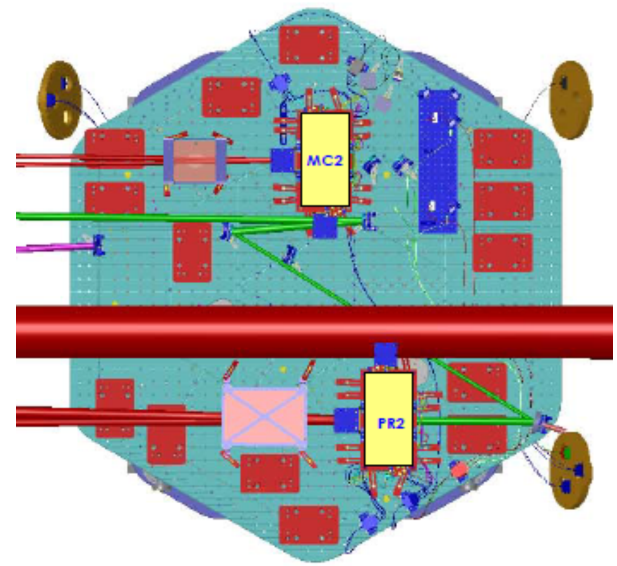
UNIVERSITY of FLORIDA

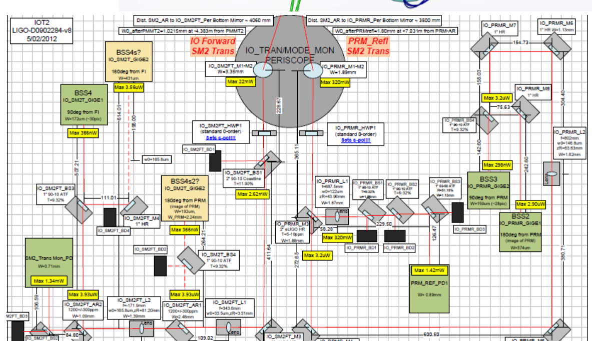
Input Optics full view





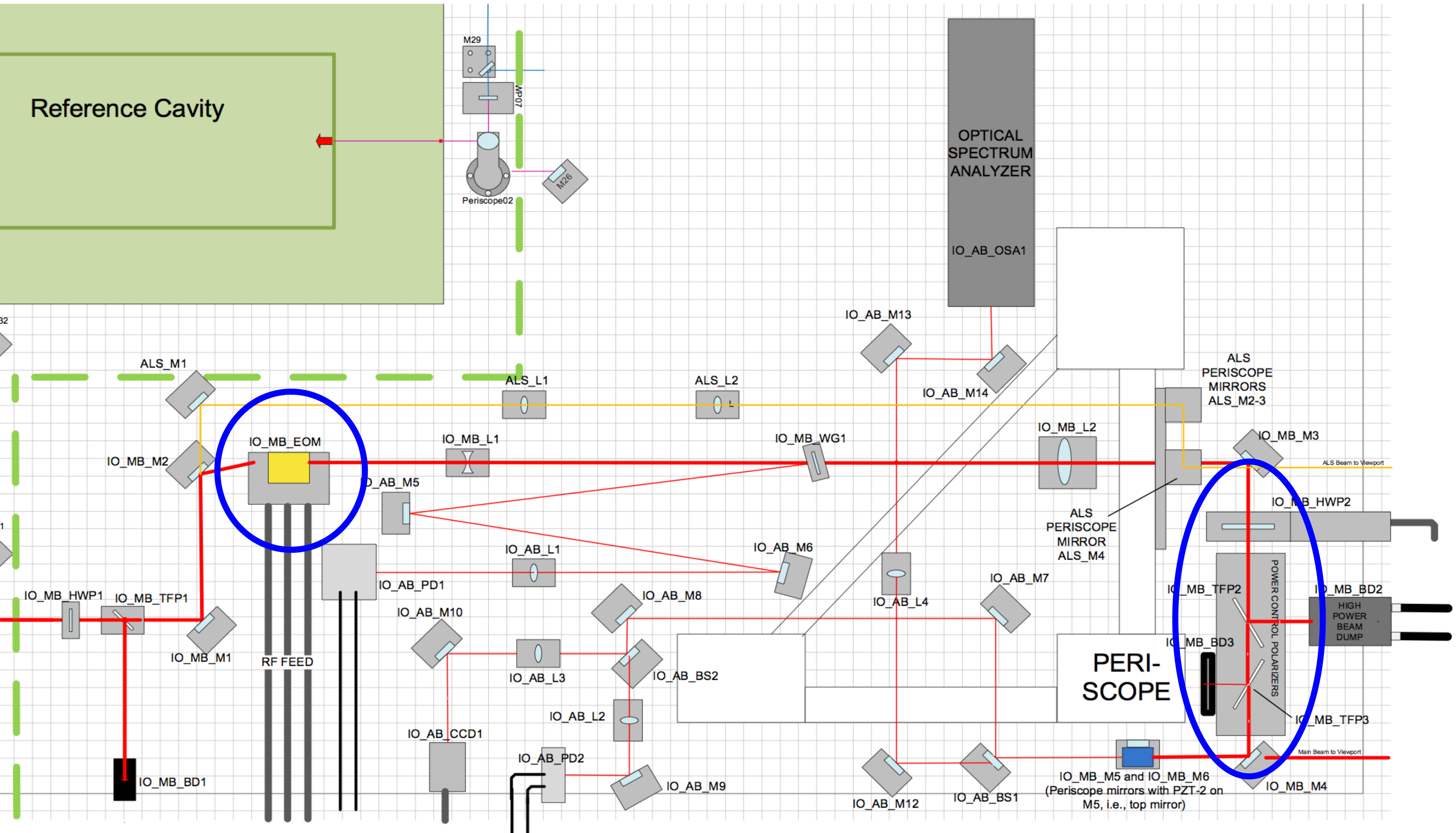






PSL-IO table

IO on the PSL table



IO on the PSL table

Electro-optic modulator

Mode matching telescope

RFAM photodiode

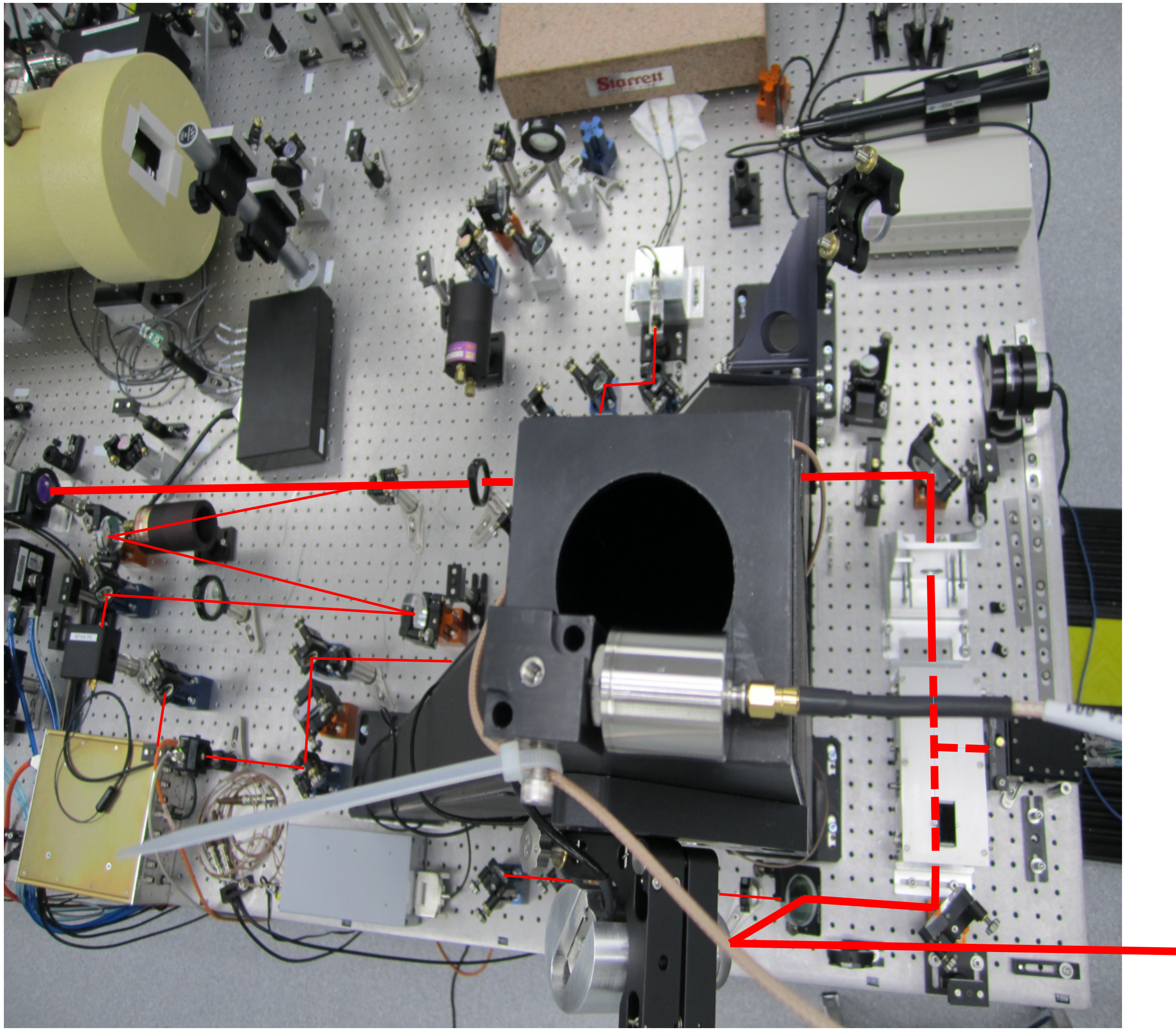
-

Power control

Beam positioning piezo

Optical Spectrum Analyzer

Beam viewing camera



EOM: Phase modulator

Electric field emerging from the PM:

$$\mathbf{E} = \mathbf{E}_0 e^{i(kL-\omega t)}$$

with $k = \omega n/c = 2\pi n/\lambda \equiv k_0 n$ and $n = \sqrt{\epsilon}$.

Suppose

$$n = n_0 + \Delta n \sin(\Omega t)$$

then phase will be modulated at Ω

$$\mathbf{E} = \mathbf{E}_0 e^{i(k_0 n_0 L - \omega t + k_o L \Delta n \sin(\Omega t))} = \mathbf{E}_0 e^{i(k_0 n_0 L - \omega t)} e^{iA \sin(\Omega t)}$$

with $A = k_o L \Delta n$. If A is small

$$e^{iA\sin(\Omega t)} = 1 + iA\sin(\Omega t) + \ldots = 1 + \frac{A}{2}\left[e^{i\Omega t} - e^{-i\Omega t}\right] + \ldots$$

making

$$\mathbf{E} = \mathbf{E}_0 e^{ik_0 n_0 L} \cdot \left\{ e^{-i\omega t} + \frac{A}{2} e^{-i(\omega - \Omega t)} - \frac{A}{2} e^{-i(\omega + \Omega t)} \right\} + \ldots$$

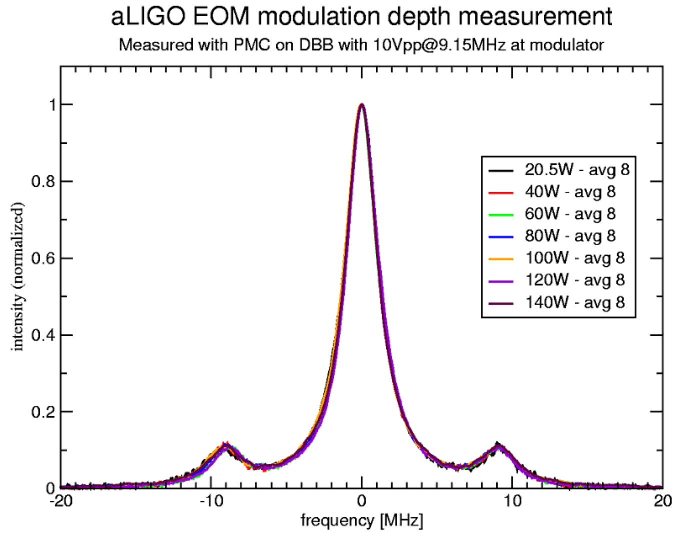
The frequency spectrum contains the carrier at ω, sidebands at $\omega \pm \Omega$, plus …

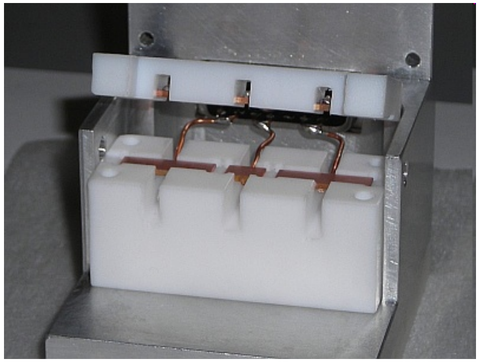
Note: The intensity in all of these is not time varying:

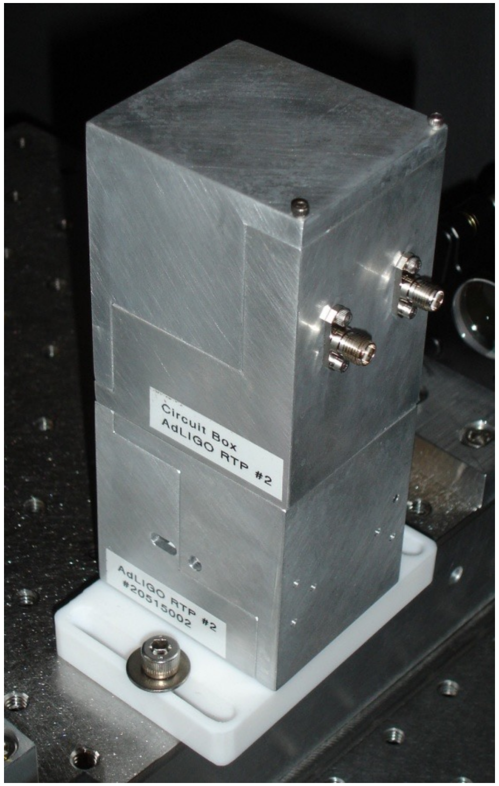
$$I \equiv \mathbf{E} \cdot \mathbf{E}^* = E_0^2$$

Electro-optic modulator

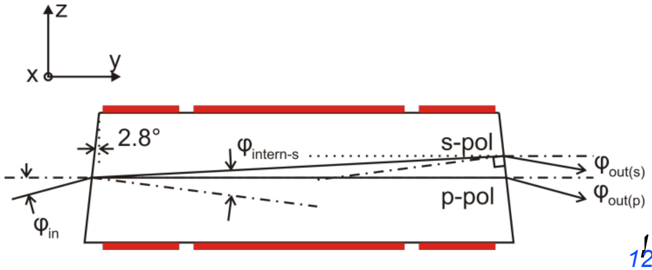
- Modulators use rubidium titanyl phosphate (RTP)
  - » Electro-optic response similar to $LiNbO_3$
  - » low absorption => low thermal lensing





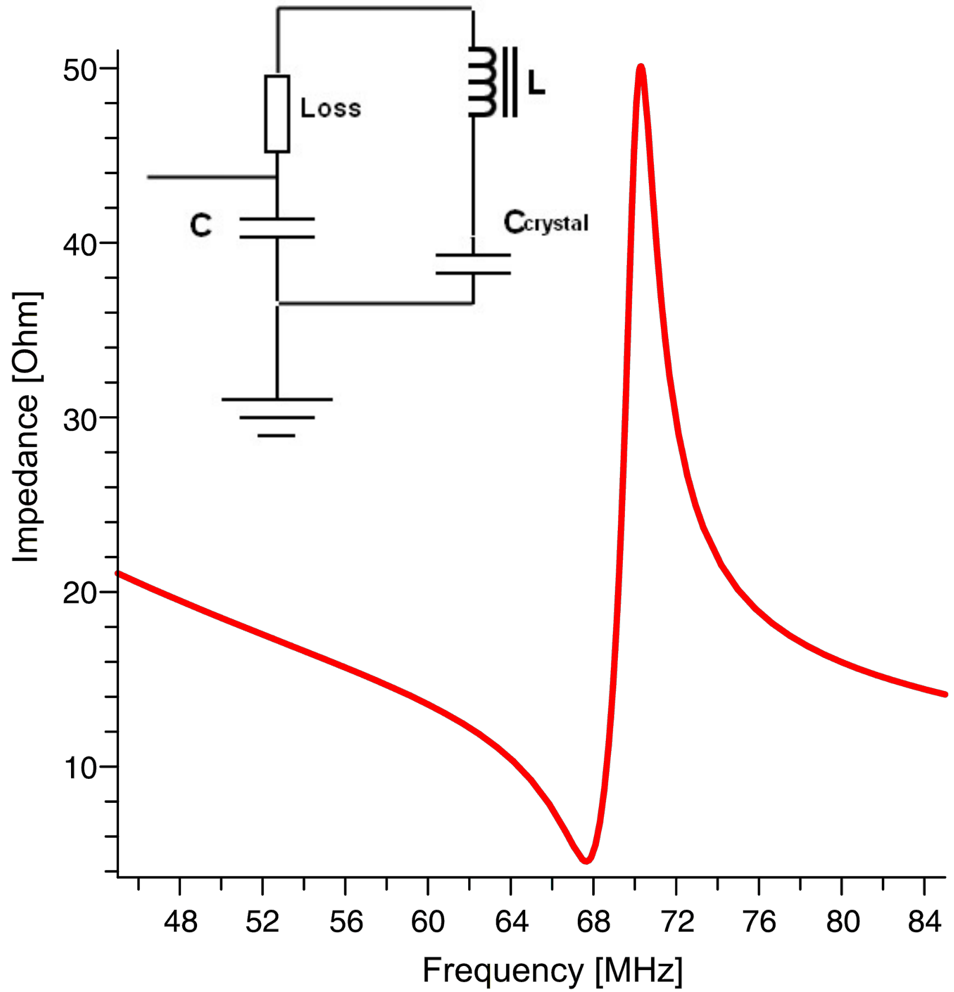


- Multiple electrode configuration
- Wedge, to reduce RFAM from polarization impurity
- RF matching circuit in separate housing
- Installed in enhanced LIGO at both sites

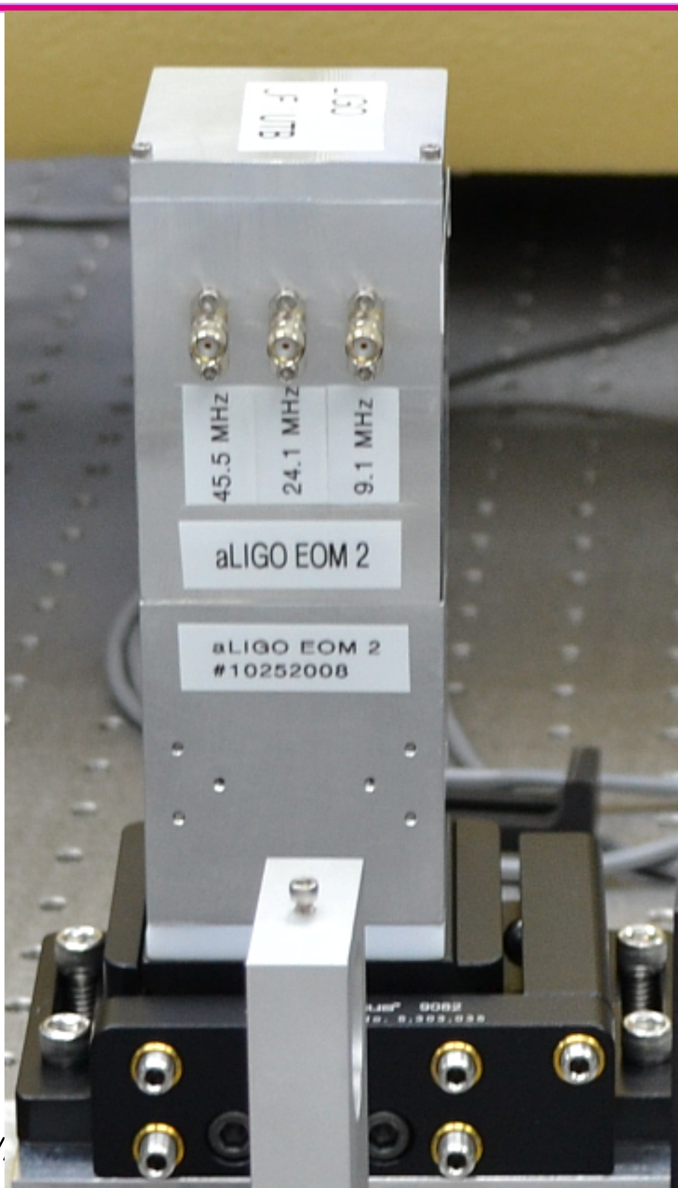


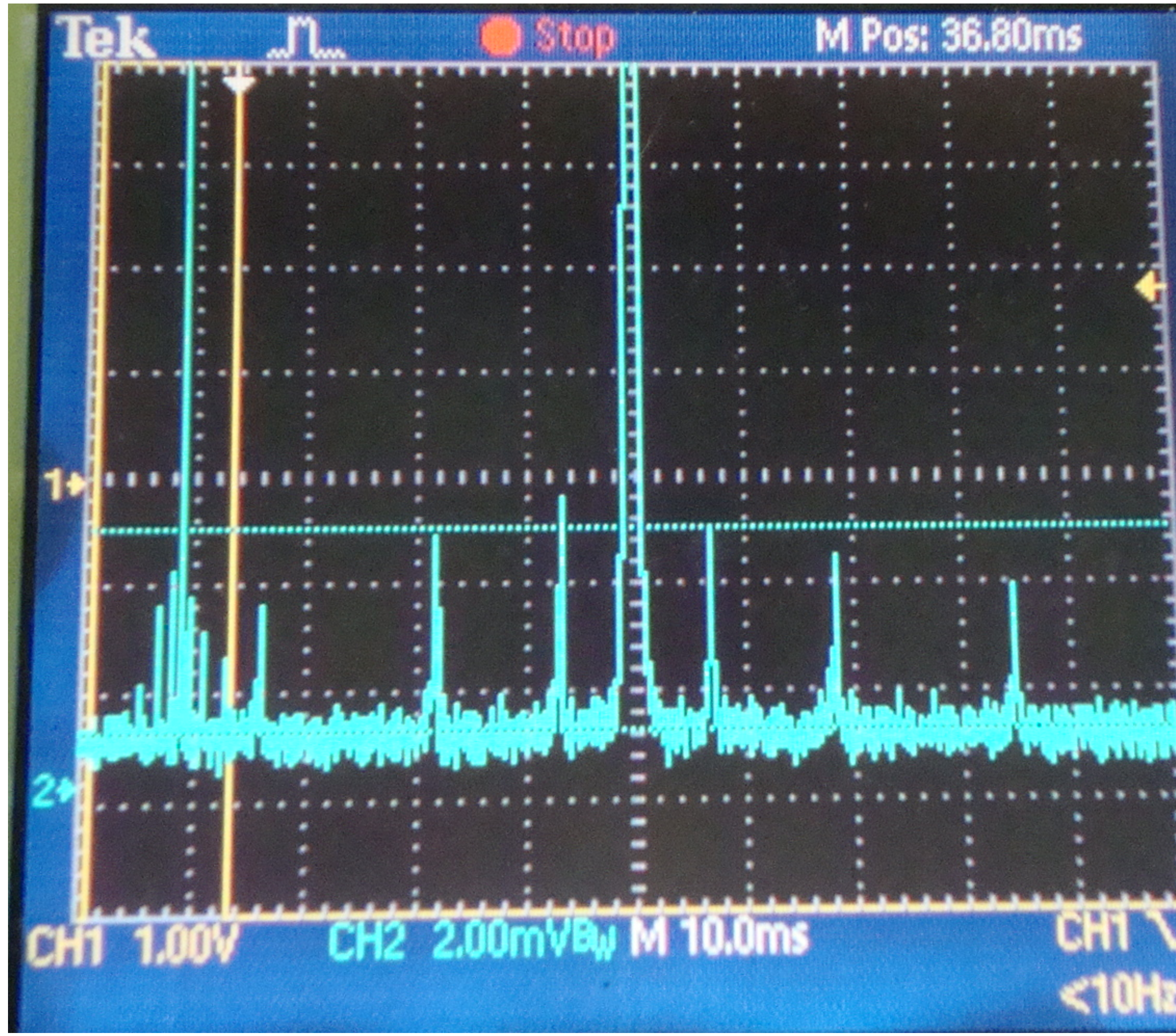
Resonant circuit

- Impedance matching circuit in separate housing.
- Resonant circuit with 50 Ω input impedance.
- Three resonant circuits:
  - » 24.5 / 33.0 / 61.2 MHz



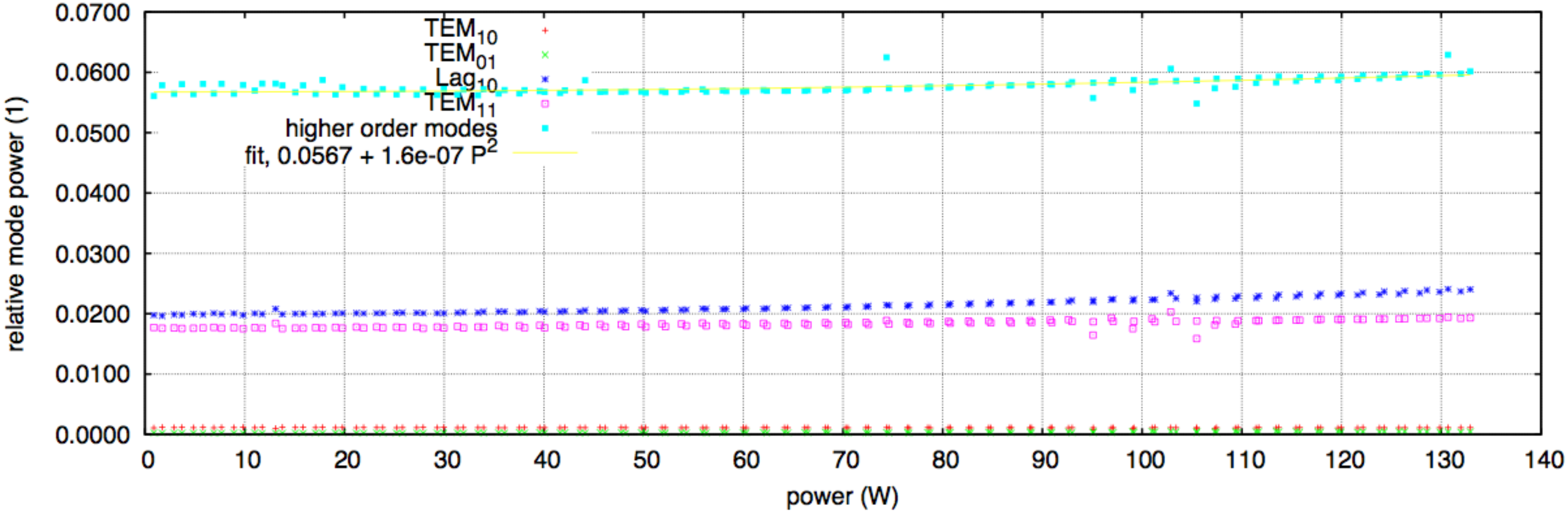
LIGO 3 RF modulators in one box

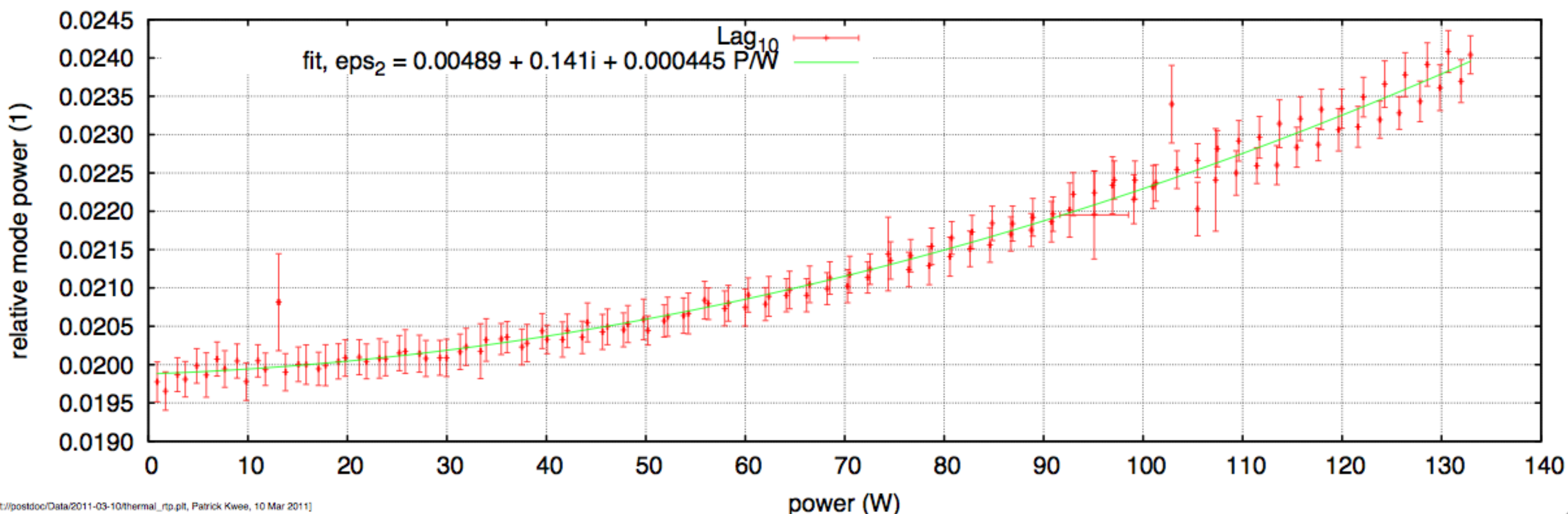




Thermal Lensing in RTP

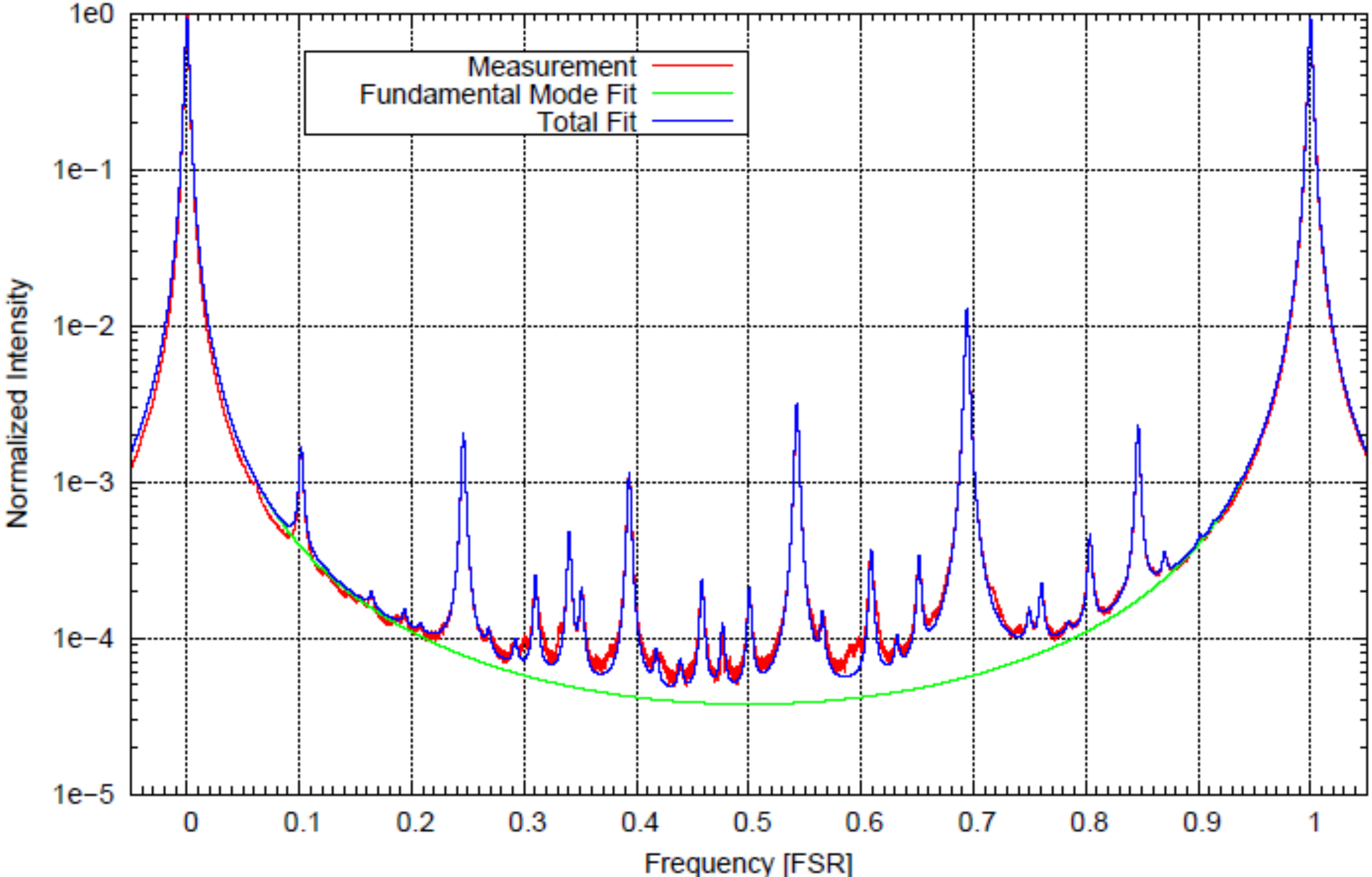
Data from Patrick Kwee, AEI



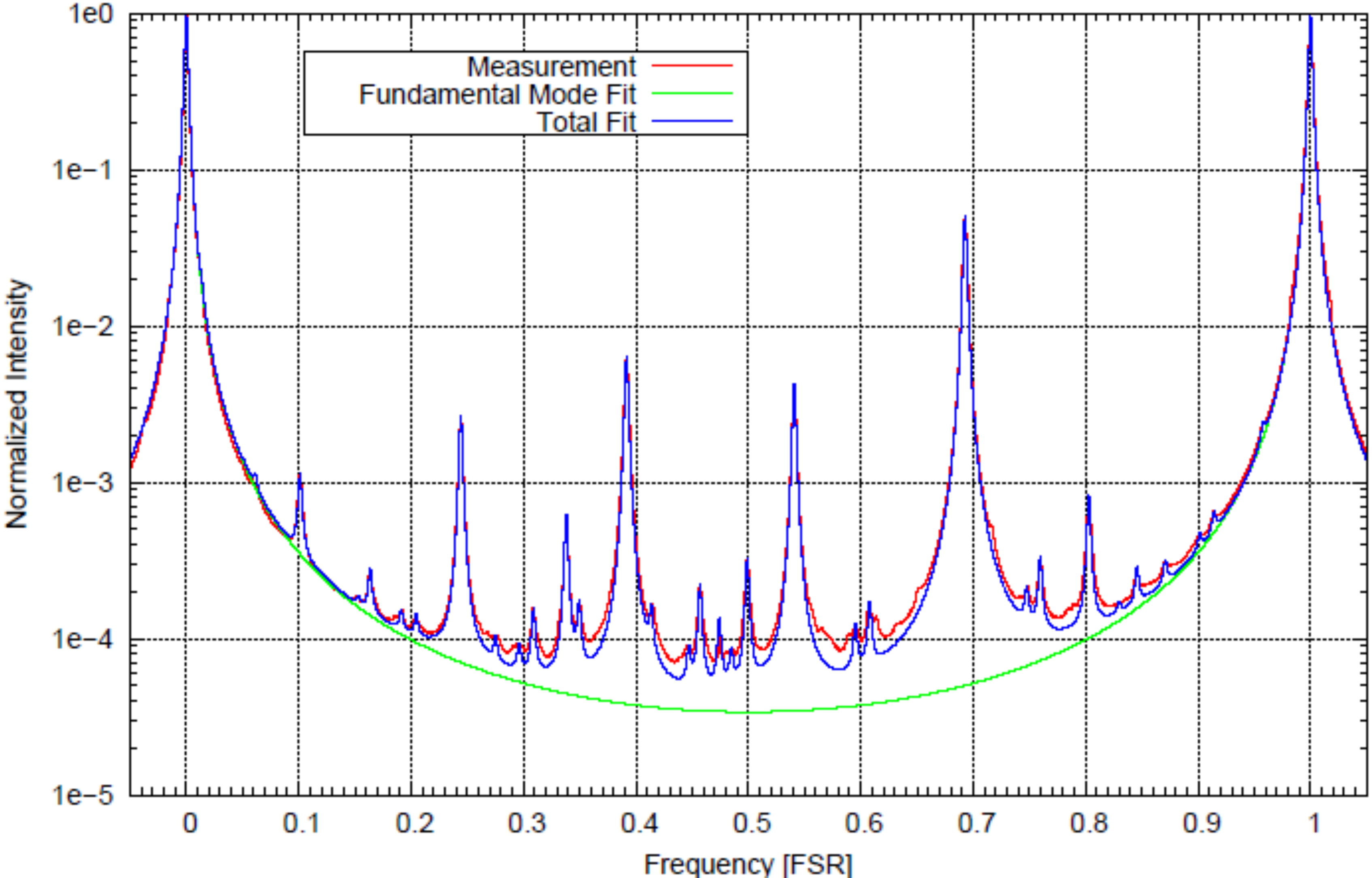


[git://postdoc/Data/2011-03-10/thermal_rtp.plt, Patrick Kwee, 10 Mar 2011]

Mode scan at 20 W

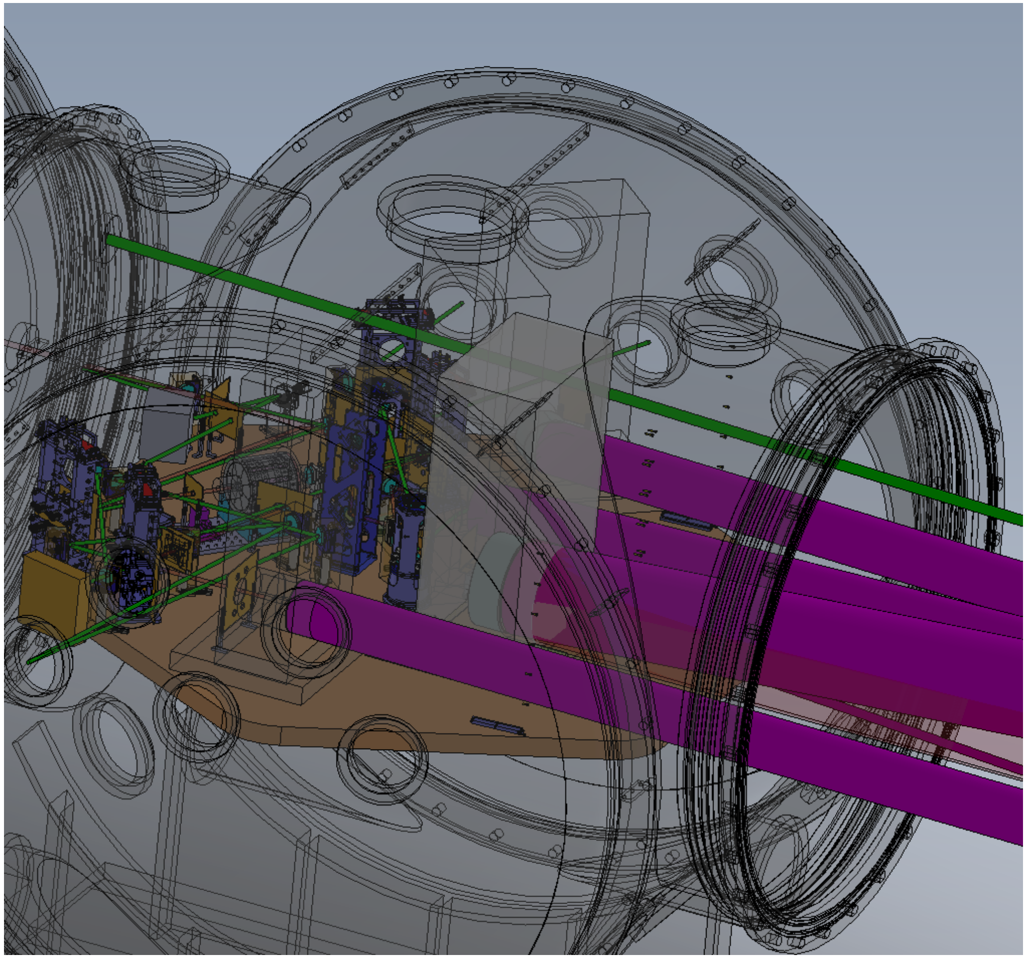


Mode scan at 140 W



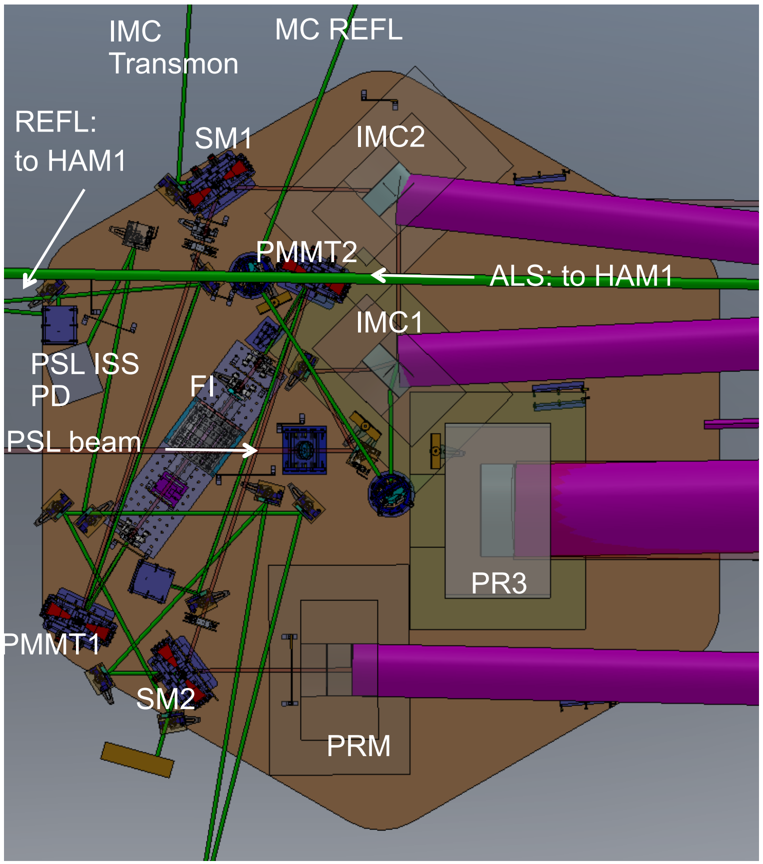
IO: Into the vacuum

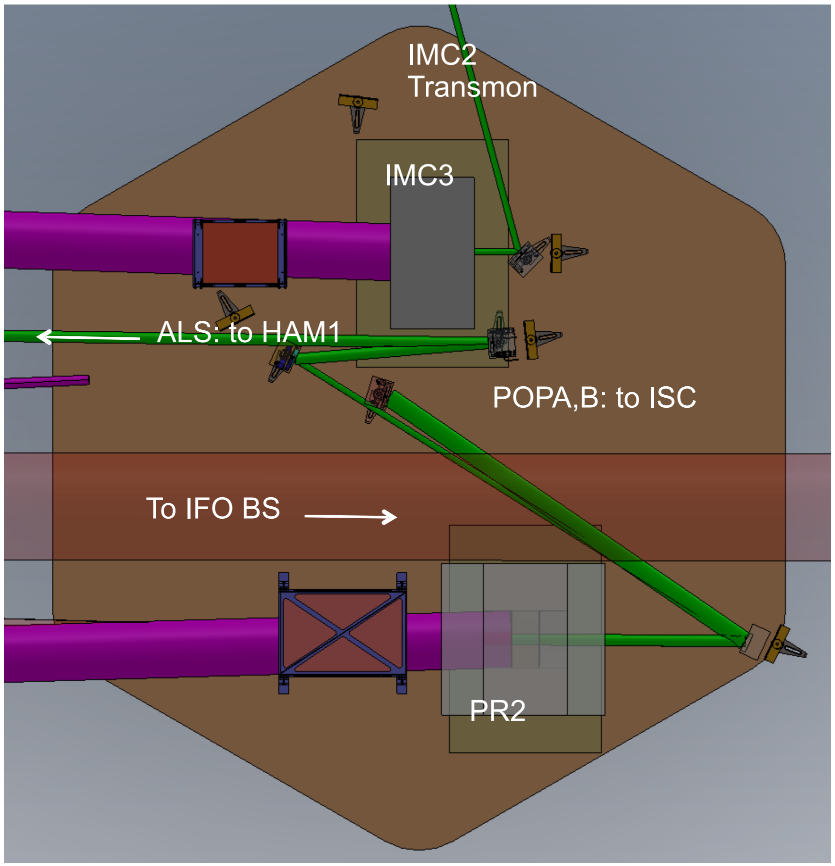
- Most of the IO is located in HAMs 2 and 3
- In-vacuum layout is dense and complex, especially in HAM 2



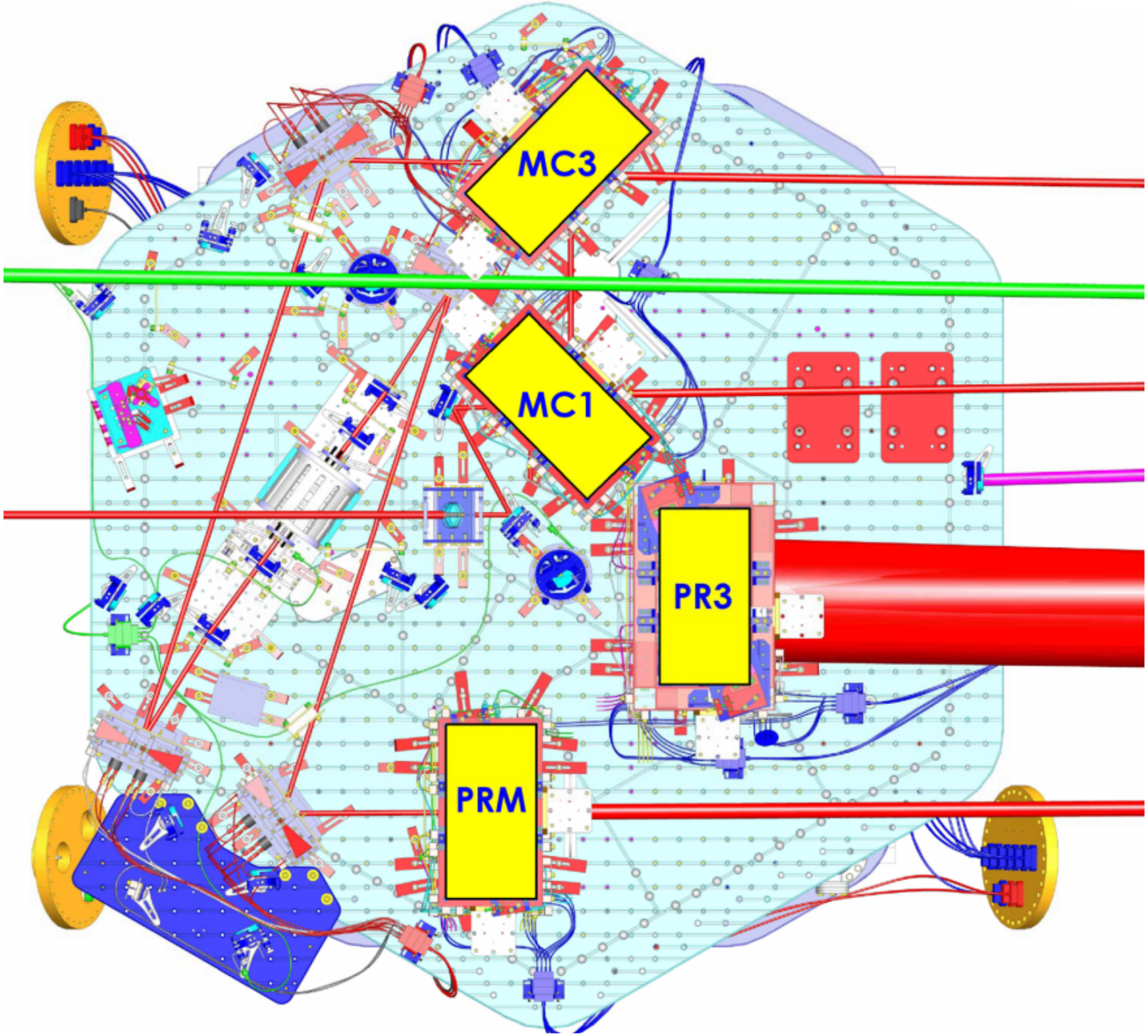
Parts installed in vacuum chambers with incredible precision

HAM 2 and 3

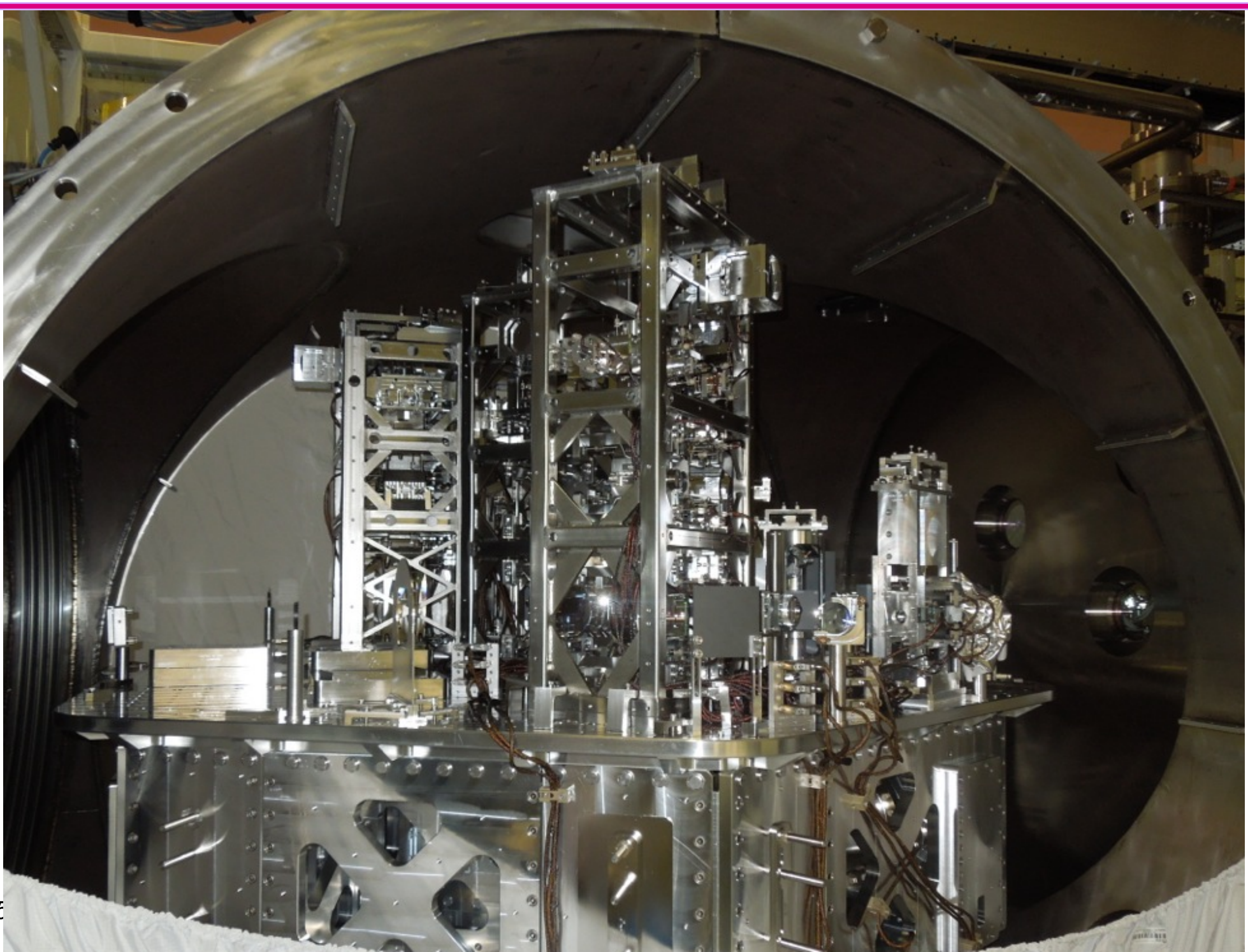

IMC
Transmon
MC REFL
REFL:
to HAM1
SM1
IMC2
PMMT2
ALS: to HAM1
IMC1
PSL ISS
PD
FI
PSL beam
PR3
PMMT1
SM2
PRM


IMC2
Transmon
IMC3
ALS: to HAM1
POPA,B: to ISC
To IFO BS
PR2

HAM2

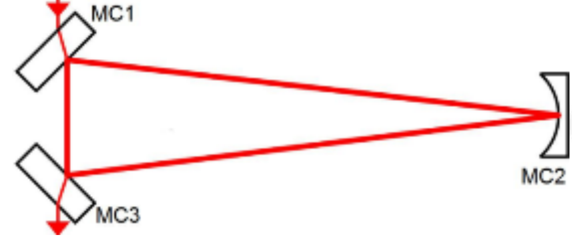


HAM 2

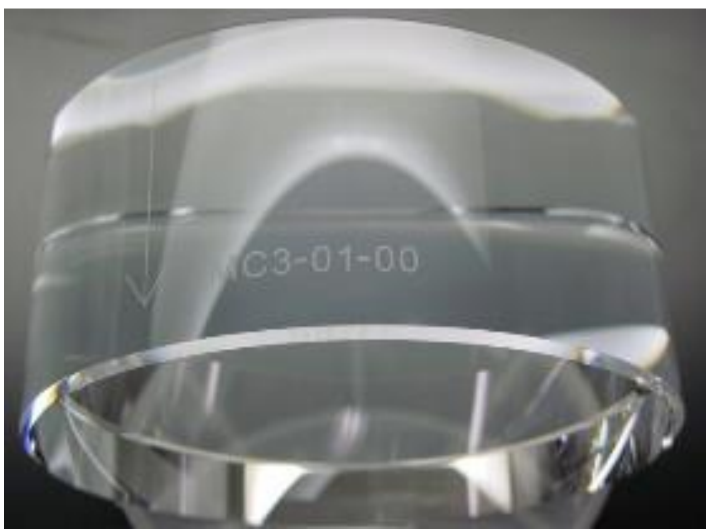


LIGO

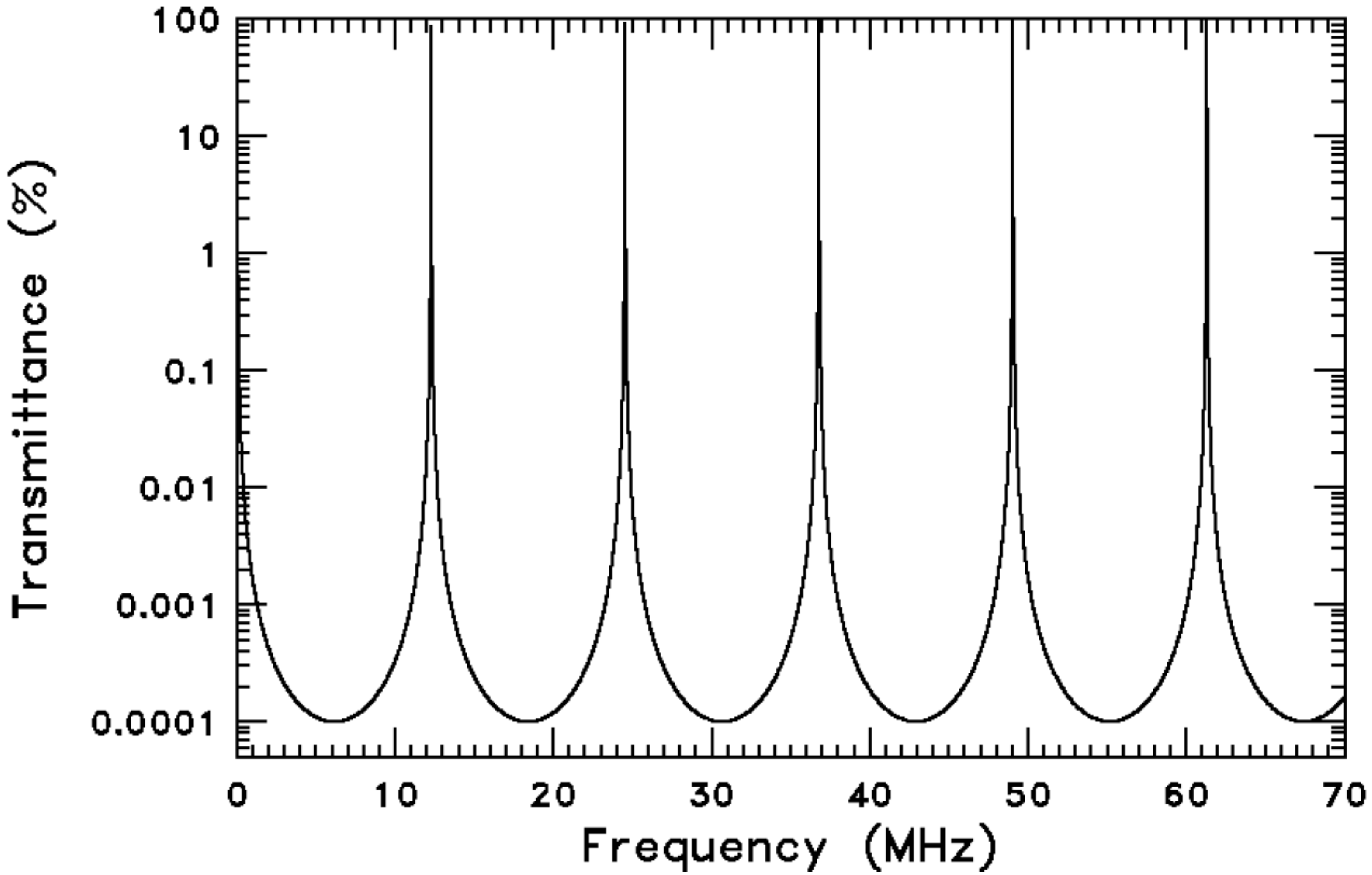
Input Mode Cleaner



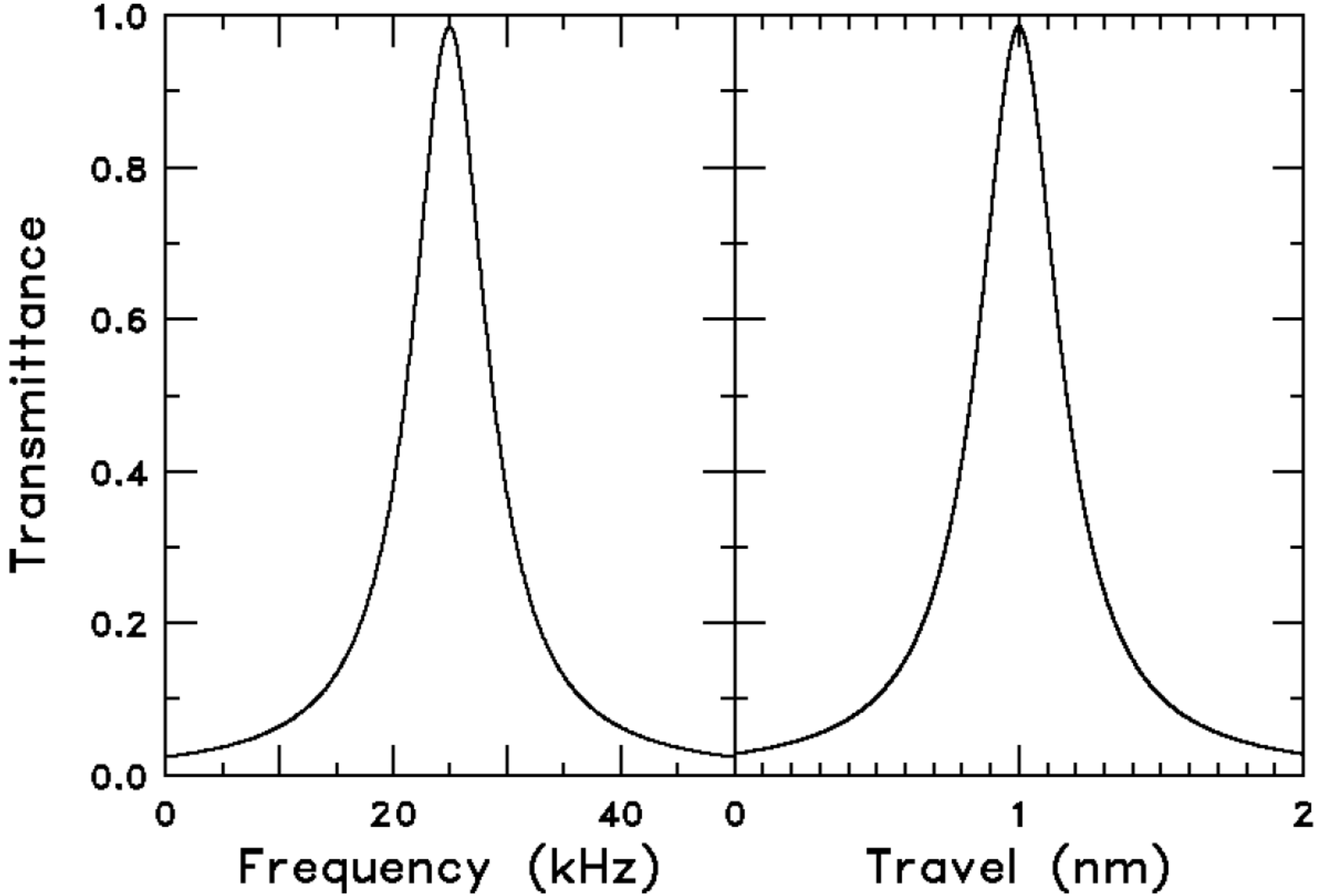
- Triangular ring cavity
- Stabilize pointing
- Frequency reference
- *L/2* = 16.5 m; Finesse = 520



Mode cleaner FSR



T vs freq vs length



Reject high-order modes

For TEM_{lm} Gaussian modes, the resonances occur at frequencies

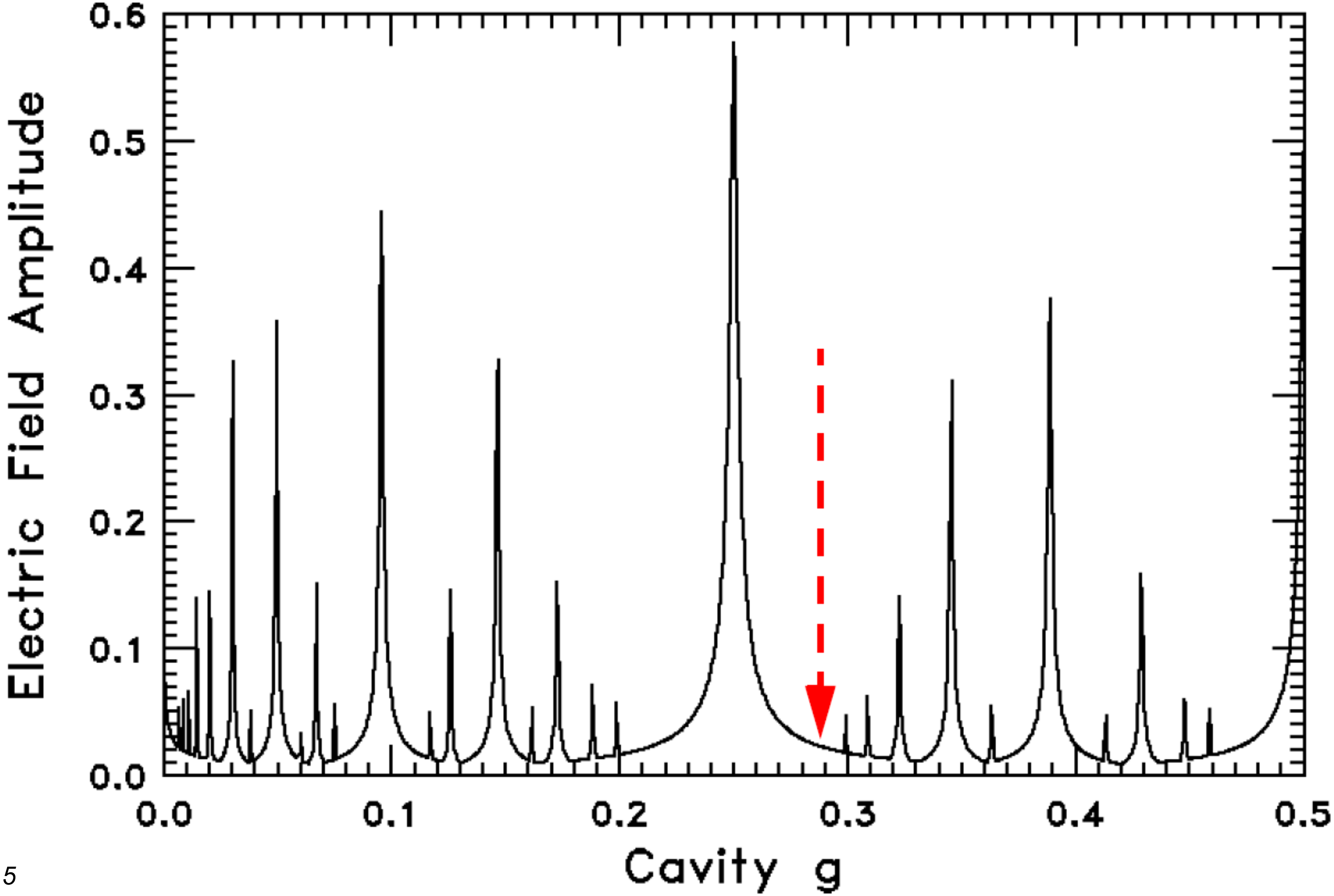
$$\nu_{lm} = \frac{c}{2L}\left[n - \frac{1}{2} + \frac{l+m+1}{\pi}\operatorname{acos}(\sqrt{g})\right]$$

where $g = 1\text{-}L/R$ with R the radius of curvature of the curved mirror. The resonator is adjusted for resonance with the TEM_{00} mode; this sets the value of n (of order 10^7). The radius of curvature (and hence g) is chosen so that the resonance condition is not satisfied for $l \neq 0$ and $m \neq 0$ for any $\{n,l,m\}$. The condition is

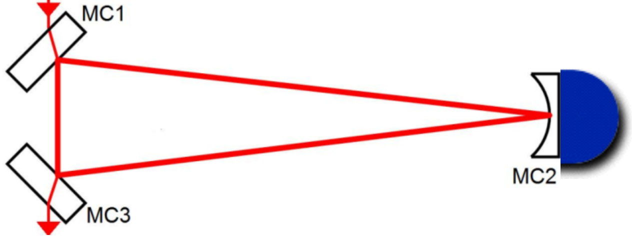
$$\frac{l+m}{\pi}\operatorname{acos}\sqrt{g} \neq integer + \varepsilon$$

where ε specifies the amount the higher-order mode avoids being resonant.

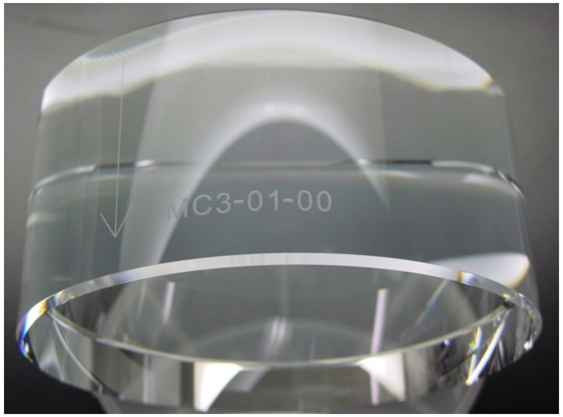
Transmission of HOM



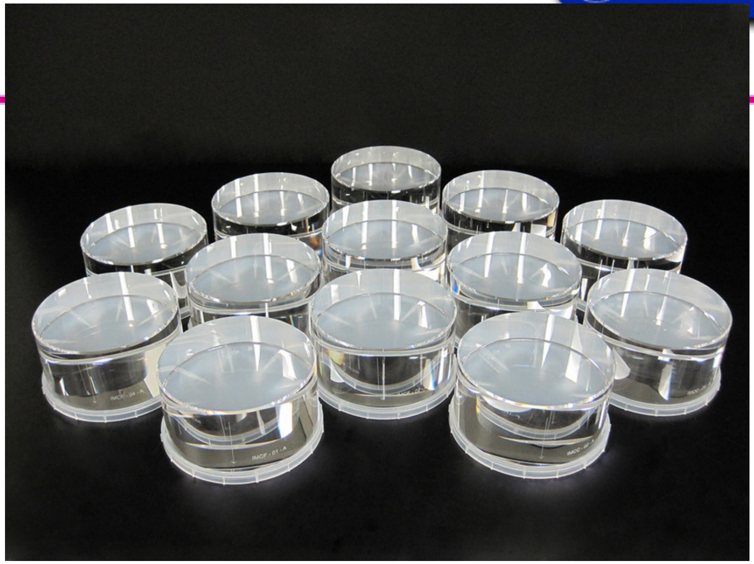
HAM triples

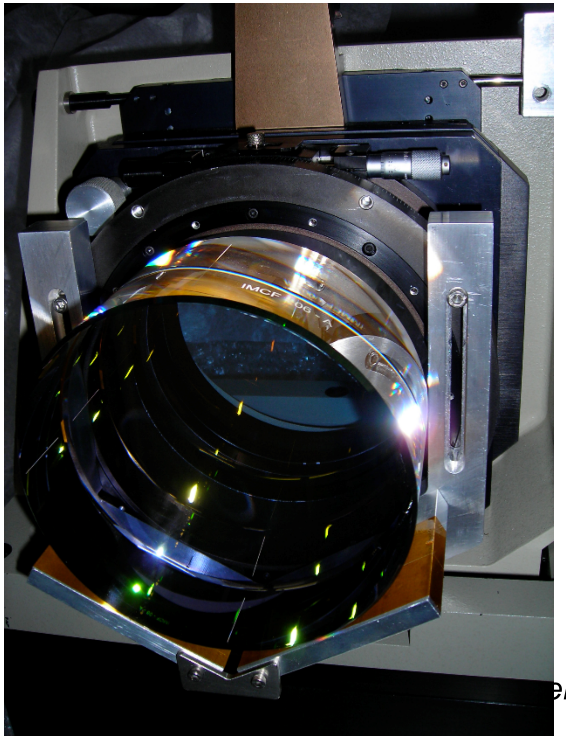


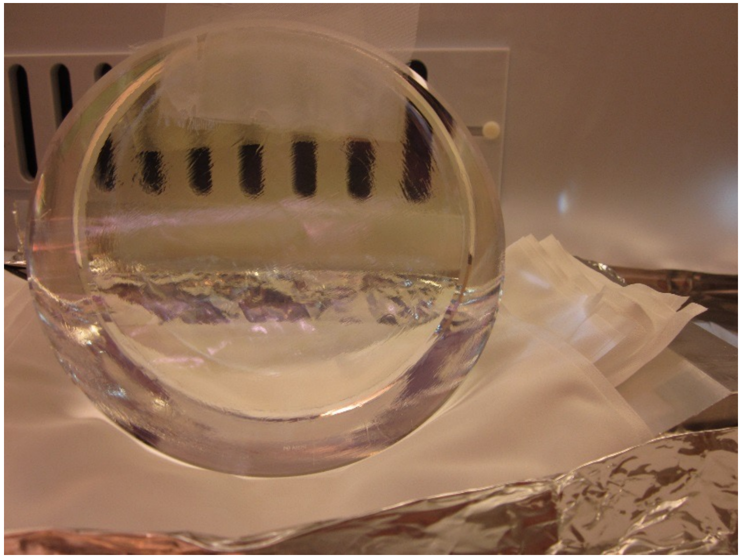
- Mirrors suspended as 3 pendulums in series for seismic isolation, control
- Mirrors 15 cm diameter x 7.5 cm thick -- 3 kg
- 12x heavier than iLIGO, to limit radiation pressure noise



IMC mirrors

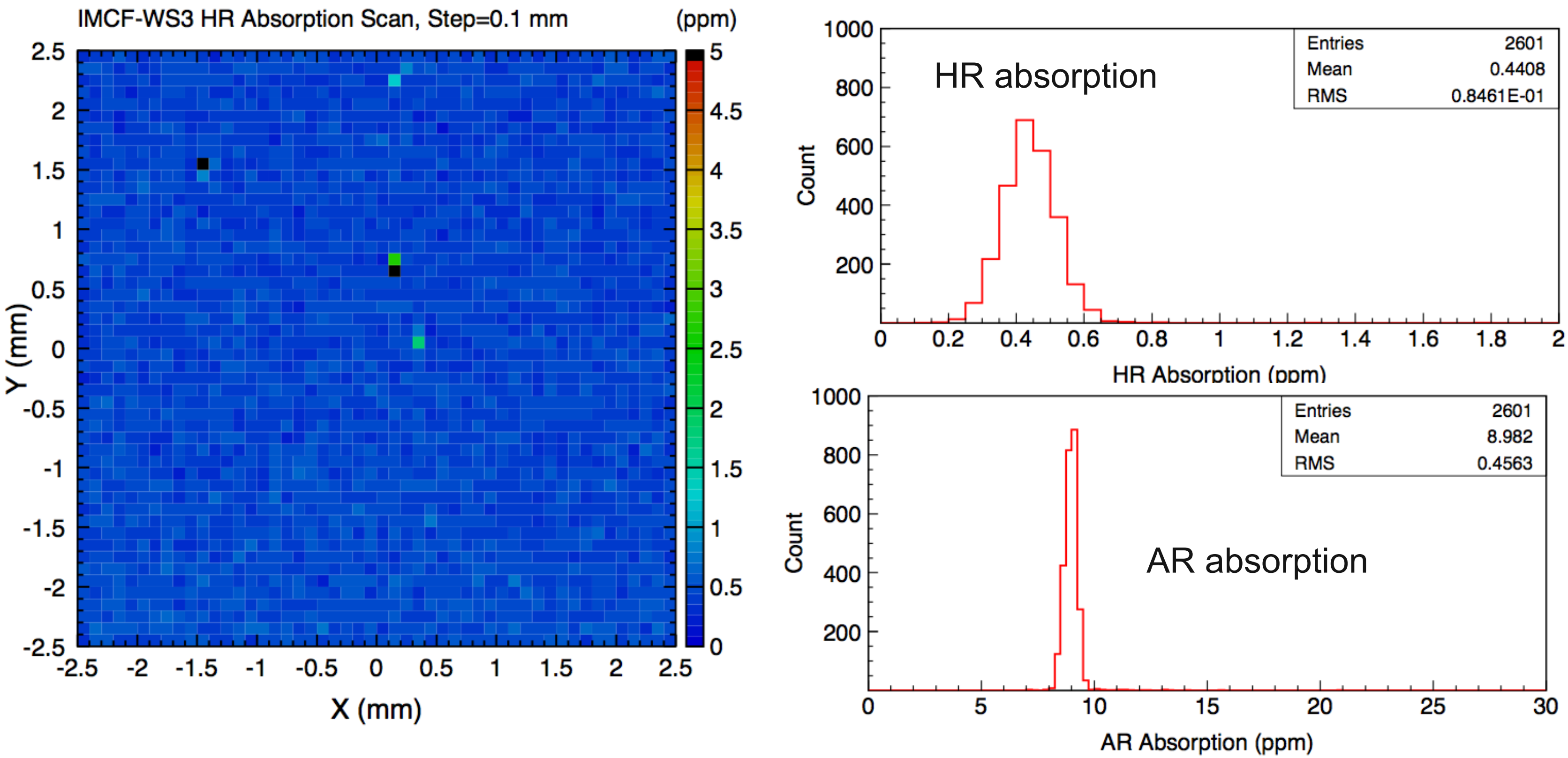






IMC Mirror Absorption

MCF-WS3 witness sample absorption scan



IMC mirror phase maps

Measurement Parameters

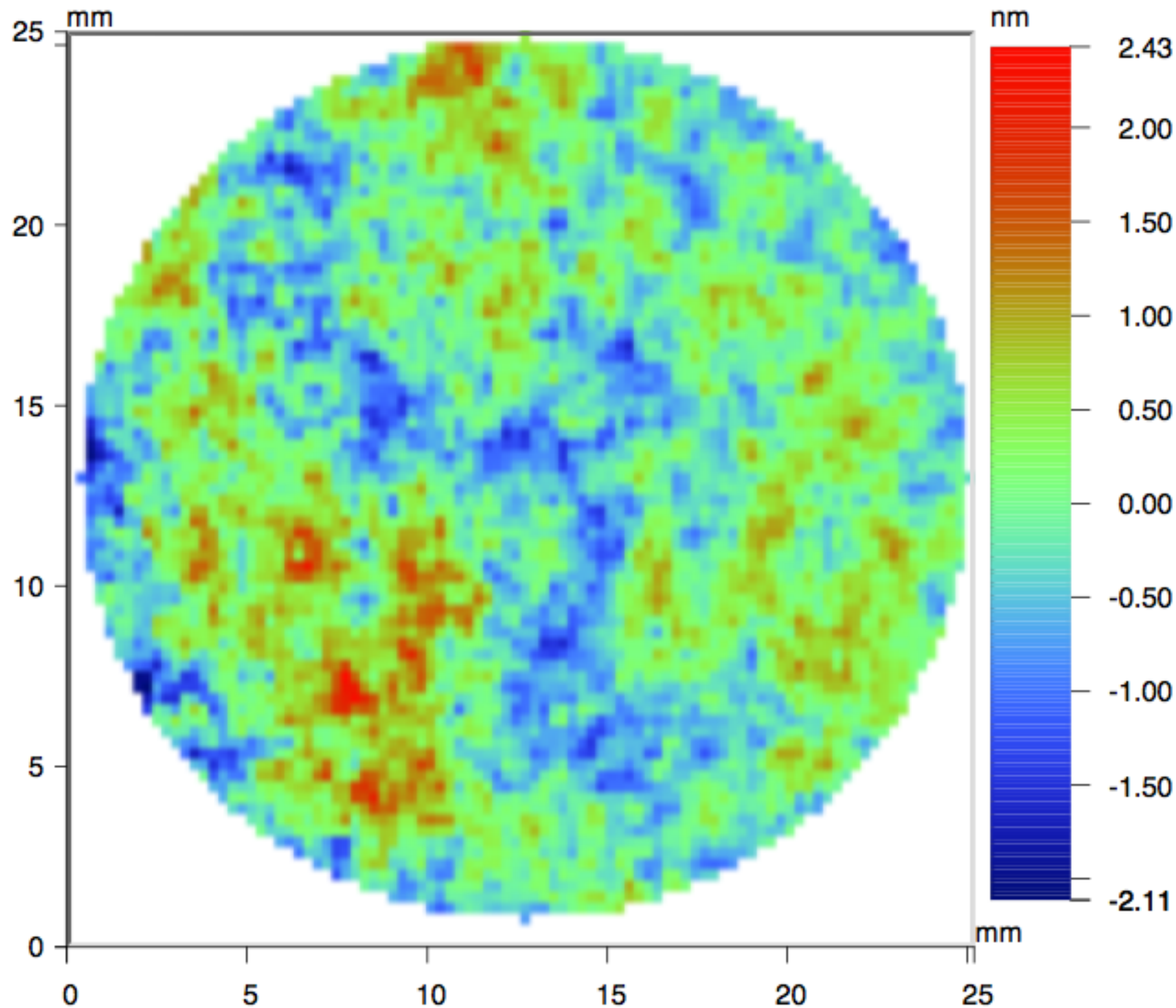
File:	WYK36
Wavelength	1.06 um
Wedge	0.50
X/YSize	96 X 83
Pixel size	265.05 um
Date	09/22/2010
Time	13:40:08
Averages	16

Analysis Results

Ra	0.457 nm
Rms	0.574 nm
20 Pt. PV	3.431 nm
2 Pt. PV	4.54 nm

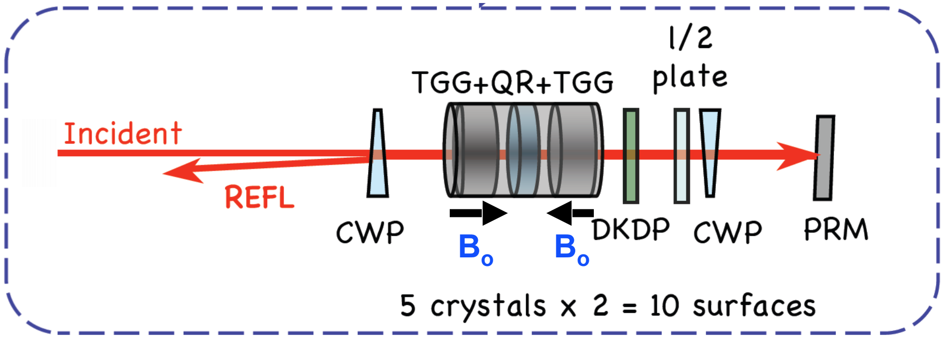
Analysis Parameters

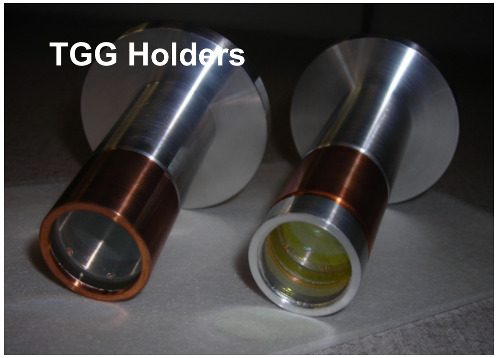
Terms	Tilt Power Astig
Masks:	Det Anl Trm Masks
Filtering	DBP (0.04/2/mm)
Data Restore	Yes
Valid Points	5895

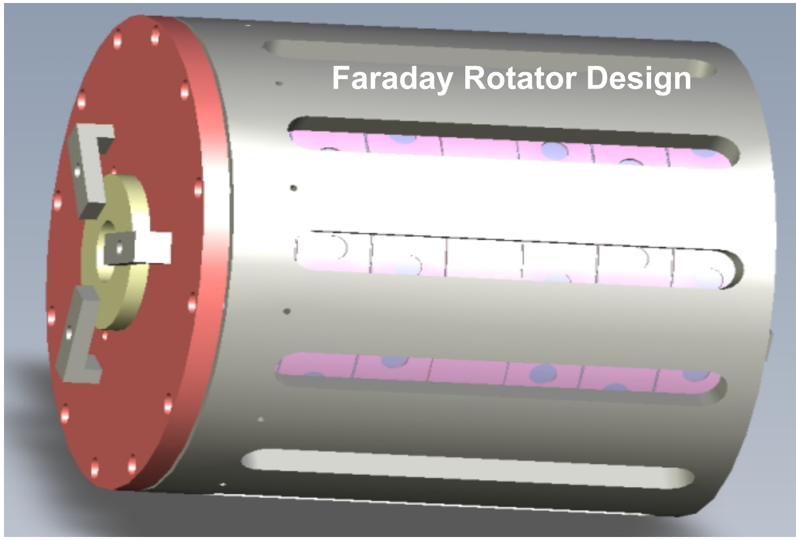


Faraday Isolator

- IAP/UF design and construction
- Passively compensated (for depolarization and thermal lensing)
- Consists of 2x calcite polarizers, 2x TGG crystals, quartz rotator, λ/2 plate and –*dn/dT* DKDP thermal compensator
- Observed >50 dB isolation (in lab)
- Faraday installed in enhanced LIGO
- 25 dB isolation, 1-18 W.
- 20 μrad REFL drift.







IAP = Institute of Applied Physics, Nizhny Novgorod
TGG = terbium-gallium garnet
DKDP = deuterated potassium dihydrogen phosphate, KD_2PO_4

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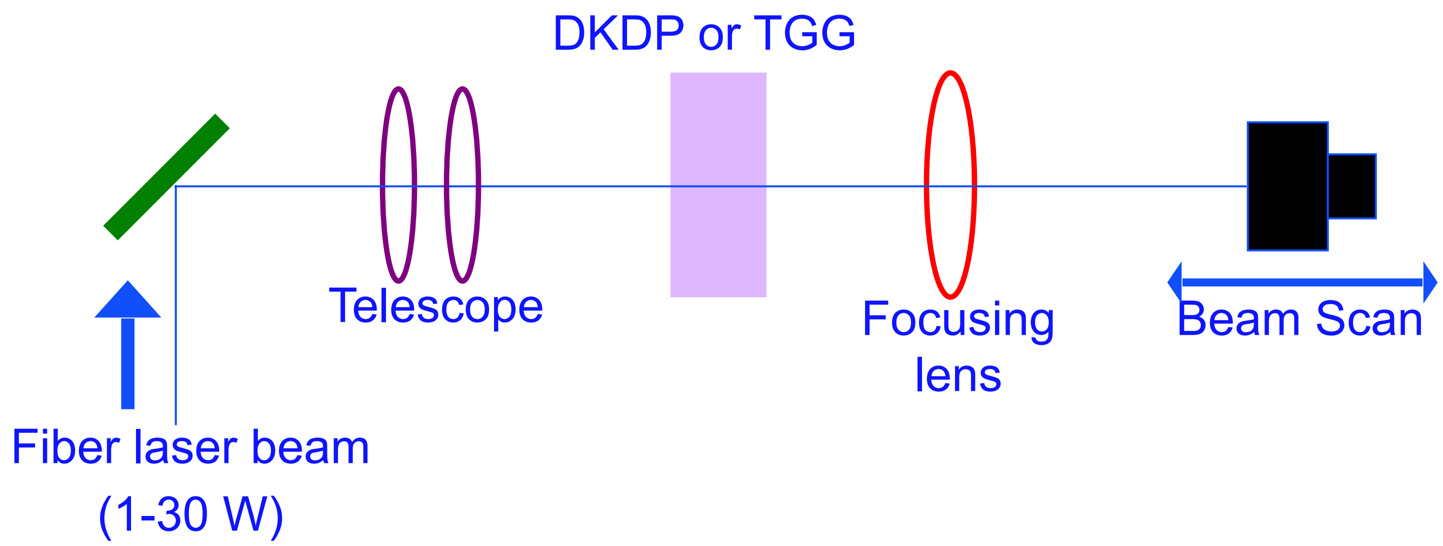
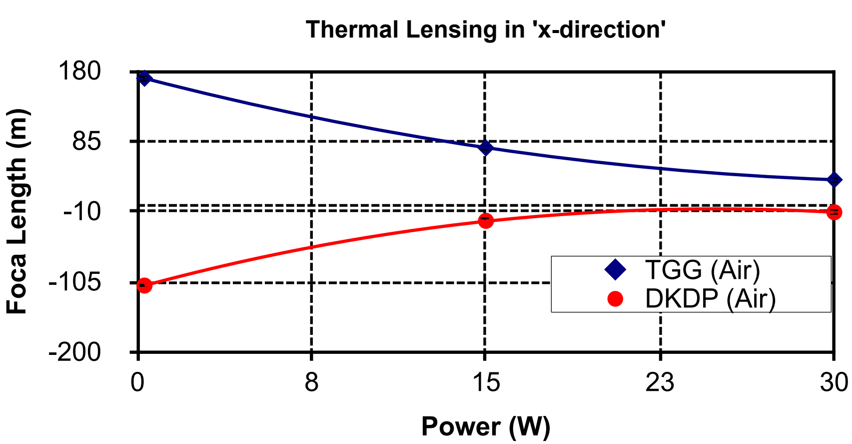
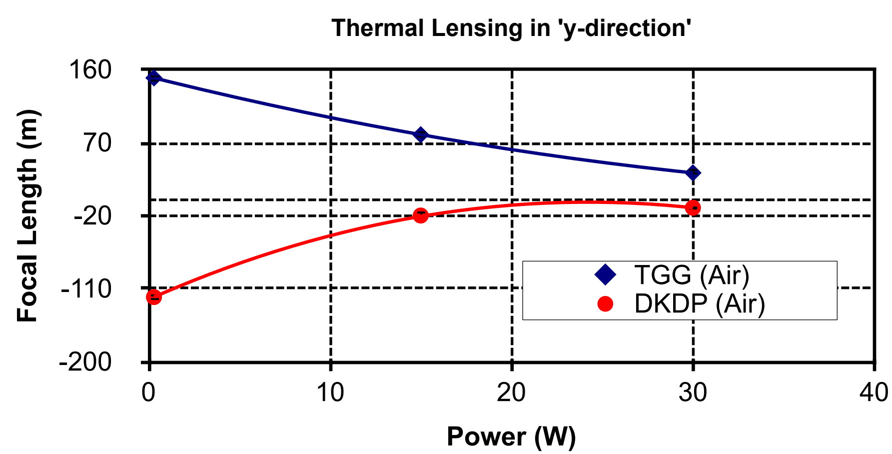
Thermal lens created by TGG and DKDP



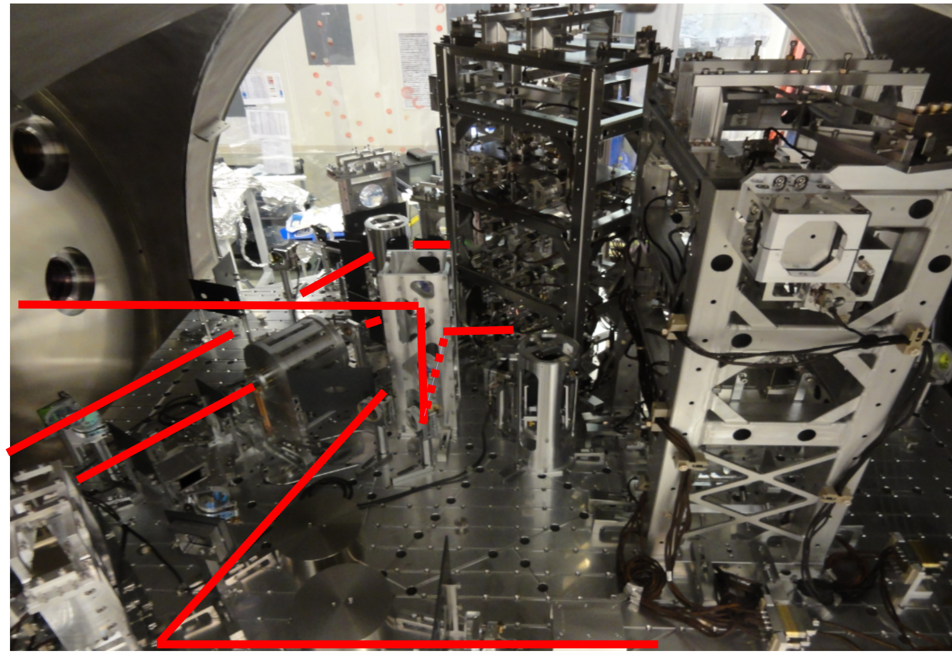


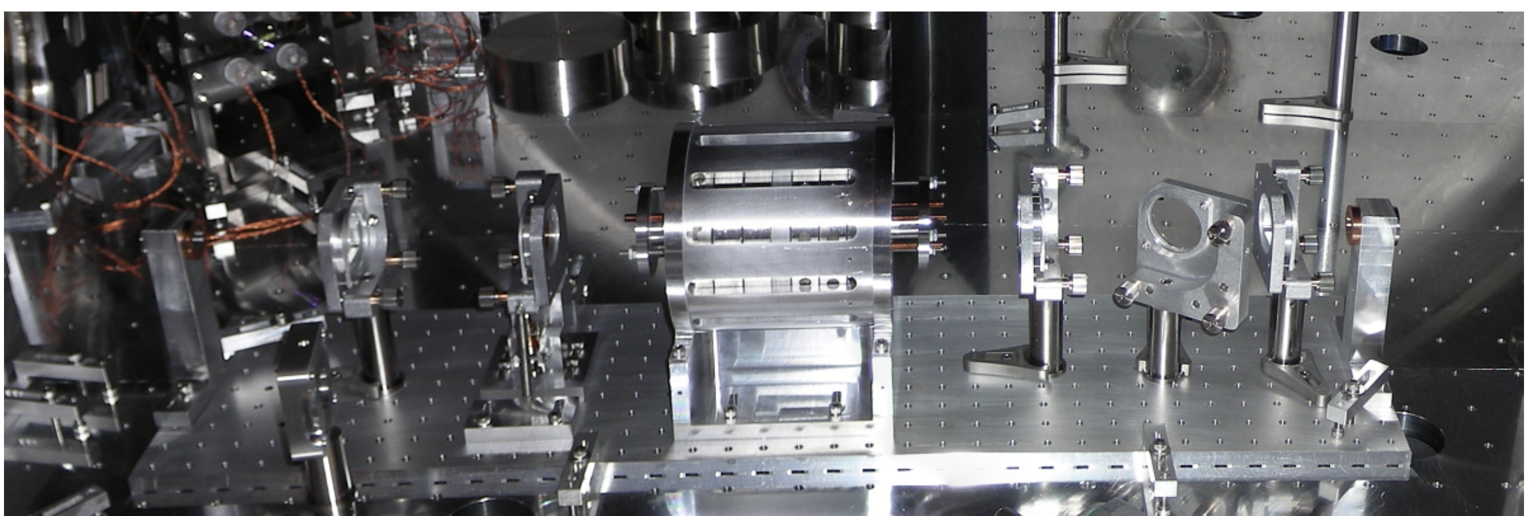


Faraday isolator

Faraday

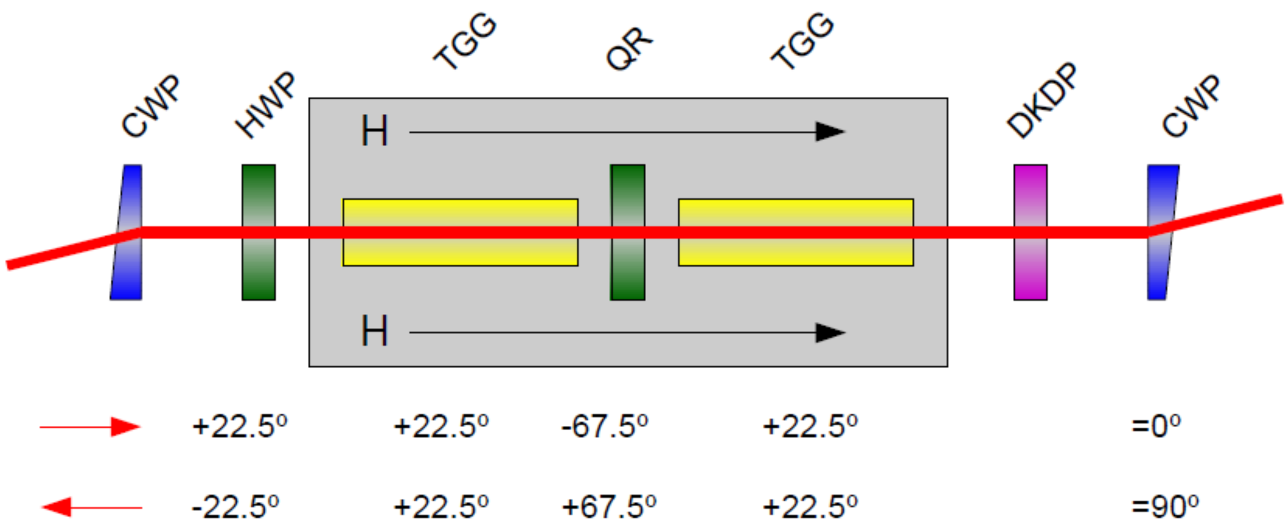
Palashov et al JOSA B (2012)





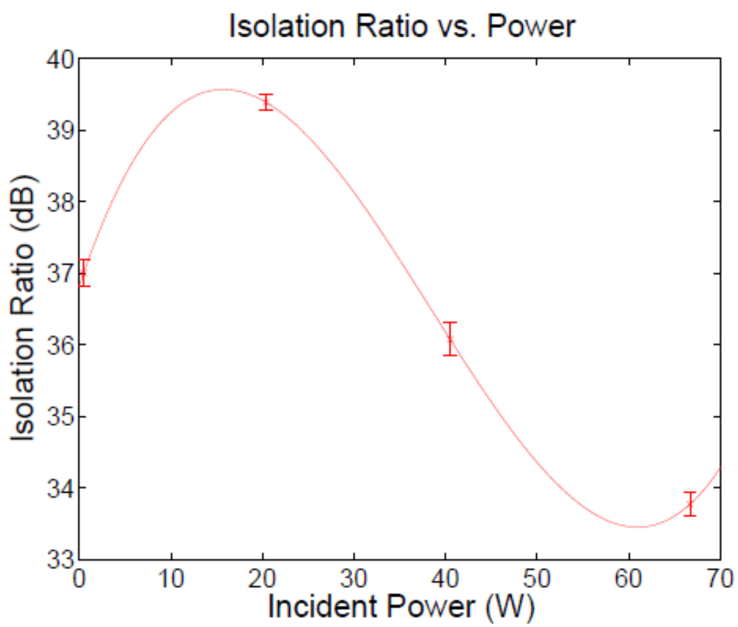
Faraday design

- Same as eLIGO except for removal of the thin film polarizer.
- Calcite wedge polarizers for low loss and high isolation.
- Double TGG with quartz rotator design for thermal depolarization compensation.
- DKDP (negative dn/dT) for thermal lens compensation.
- Half wave plate is adjustable from the control room.



Performance

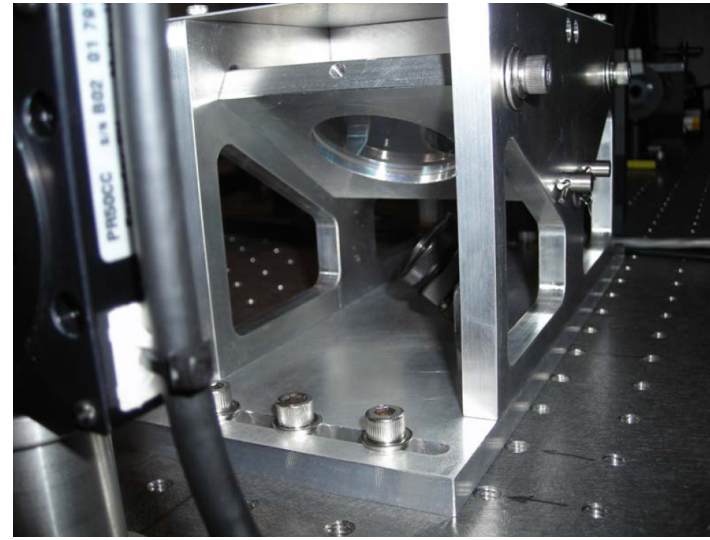
- Stress induced linear birefringence is the strongest effect with temperature
- The beam is rotated with a quartz rotator between the two TGG crystals to compensate partially for the linear birefringence.
- The FI is optimized for isolation at 20 W.



iLIGO[5]	26 dB
eLIGO[5]	35 dB

Other items

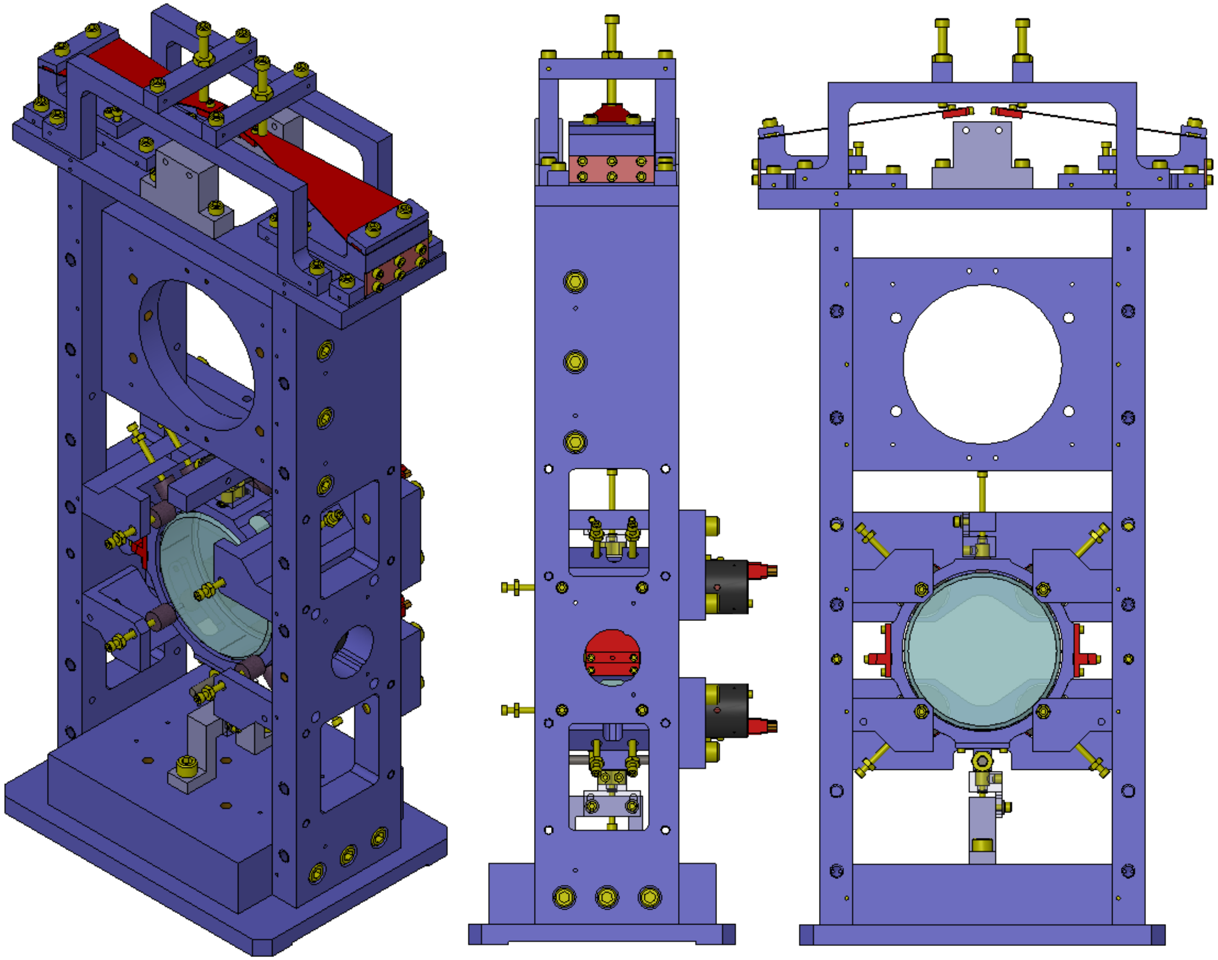
- Power control: motorized waveplate and 2x thin-film polarizers on PSL table, behind EOMs. *T* ~ 98%. Extinction ratio 140,000:1
- Mode-matching to IMC: 2 lens telescope on PSL table
- Periscope: Oil derrick
- HAM Aux
-



PSL = pre-stabilized laser;
EOM = electro-optic modulator
IMC = input mode cleaner
HAM = vacuum chamber

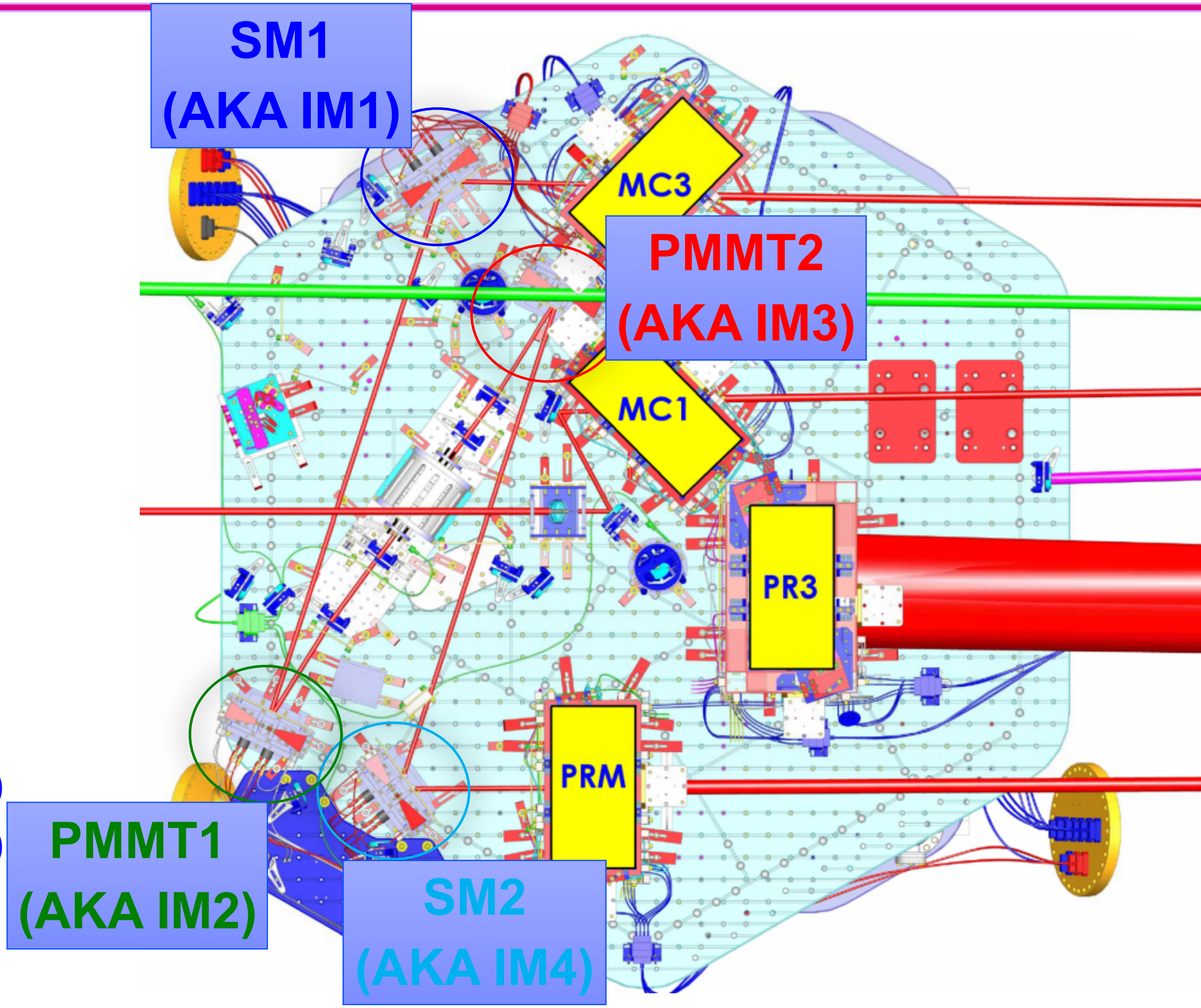
HAM Aux (Giacomo)

- Single stage (outgrowth of SOS)
- 4 OSEMs
- 3 inch optic in an aluminum optic holder
- Blades for vertical isolation
- Eddy current dampers



HAUX locations

- 4 per IFO, all in HAM2
- They suspend steering and pre-mode-matching mirrors in the IO chain:
  - » SM1 (now IM1)
  - » PMMT1 (now IM2)
  - » PMMT2 (now IM3)
  - » SM2 (now IM4)



IO Baffles: Overview

T0900486-v5

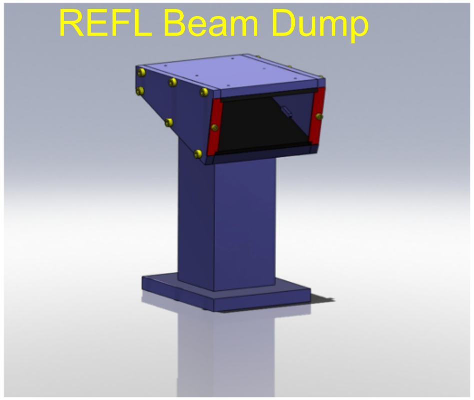
- The IO has a high density of high power lasers beams in a very confined space.
  - » It's a very dangerous place...
- The IO baffles serve two purposes:
  - » To prevent scattered light from entering sensing the interferometer and sensing photodiodes
  - » To protect the in-vacuum components from laser damage

- IO Baffle types:

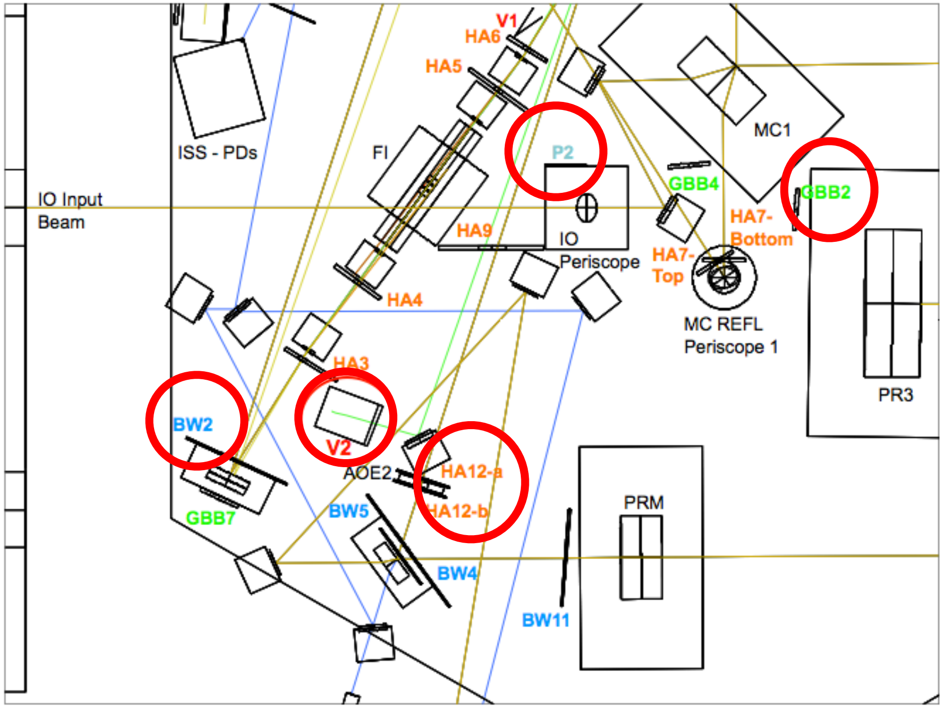
1. Beam dumps - for parking and dumping high power beams
2. Suspension baffles - for protecting suspension components
3. Hard apertures and plates - for protecting other components
4. Scraper baffles - for collecting small angle scattered light
5. Ghost beam baffles - for blocking specular reflections from AR coatings and other low power

IO Baffles

- Different materials for different power levels
  - » High power absorbing beam dumps: superpolished SiC @ Brewster angle
  - » High power 'protectors': unpolished SiC
  - » Low/medium power (< 5 W): porcelain-coated stainless steel
  - » Very low power (< 500 mW): absorbing black glass



Baffles in HAM2



Source files

Some key sources for IO:

- *P1500076*
- *E1201013*
- *G1200911*
- *G060185*
- *G070680*

Done